Water and nutrient use efficiencies of potato-based (*Solanum tuberosum* L.) rotation systems in North West Province, South Africa

by

Alex Mukiibi

Submitted in partial fulfilment of the requirements for the degree
M.Sc. (Agric.) Soil Science
In the Faculty of Natural and Agricultural Sciences
University of Pretoria

Supervisor: Prof. J.M. Steyn
Co-supervisors: Prof. M. van der Laan
Prof. A.C. Franke

November 2019

DECLARATION

I, Alex Mukiibi, hereby declare that this dissertation at the University of Pretoria is my own work and has never been submitted by myself or another person at any other University. I certify that no plagiarism was committed in writing of this work, except where duly acknowledged.

Signed ____

Alex Mukiibi

ACKNOWLEDGEMENTS

I would like to thank the **MasterCard Scholarship Program** at the University of Pretoria for funding my studies and providing continuous support throughout this journey.

I would also like to thank **Potatoes South Africa** for funding this research project, and also send my sincere gratitude to the potato growers of Louwna, North West Province for allowing me and the entire project group access their farms during the research project.

My special thanks go to my supervisor, **Prof. J.M. Steyn,** for working tirelessly in the field during data collection, providing support and advice throughout this learning process. Thank you for imparting skills in me. I also thank my co-supervisors, **Prof. M. van der Laan** and **Prof. A.C. Franke,** for their continuous advice and assistance during the entire journey.

My deep and sincere gratitude goes to my mentor, the late **Prof. Lawrence Mukiibi**, for sponsoring my college education. I would not have reached this point if it was not for his help and support.

I thank my **family**; Father **Peter Mutyaba**, Mother **Resty Namyalo**, Siblings **Ssemba**, **Jane**, **Costa** and **Ssimu**, entire **Kakindu** family, **Kizito** family, **Kabuye Angelo** family and all my **relatives** for their never-ending support, love, encouragement and sacrifices they have extended to me from the very beginning of my academic journey. I would not have reached this point without their support.

Thanks to **friends** (Agil Katumanyane, Anna Shaanika, Kizito Steven, Mbuule Florence, Maria Kyakuha, Charles Mubiru, Brian Gidudu, Henry Wandera, Moses Sebaggala) and **colleagues** (Sanele, Phinda, Seluleko, Zwane, Isaac Newton, Sukati, Zhethu, Knowledge, Nonhlanhla Simphiwe, Simon) for your support, assistance, encouragement and company. **Agil** and **Anna** thanks for editing my chapters, I highly appreciate.

I also acknowledge the support and assistance of the project members: **Ms. Nozidaba Radebe** and **Ms. Phiwe Mkhize** (University of the Free State).

I thank all people I have not mentioned here for your contribution throughout this journey.

DEDICATION

I dedicate this work to my mentor, the late **Prof. Lawrence Mukiibi**, who picked me up and educated me when things where very hard. I will never thank him enough.

I also dedicate this work to my grandmother, **Costa Nakayiza,** and late grandfather, **Joseph Magambo,** for the extraordinary love and care they have given me throughout my life.

Special dedication of this work to my foster family mother in Costa Rica, the late **Maria Esther Hernández Leon**, for the care and love she gave during my undergraduate study at EARTH University. "*Dedicación especial para mi madre anfitriona en Costa Rica, que ha fallecido* ***María Esther Hernández León****, por el cuidó y el amor que brindó durante mi estudio universitario en la Universidad EARTH*"

TABLE OF CONTENTS

DECLARATION i

ACKNOWLEDGEMENTS ii

DEDICATION iii

TABLE OF CONTENTS iv

LIST OF FIGURES ix

LIST OF TABLES xi

LIST OF SYMBOLS AND ABBREVIATIONS xv

ABSTRACT xviii

CHAPTER 1 1

GENERAL INTRODUCTION 1

1.1 Problem statement 3

1.2 Hypotheses 4

1.3 Objectives 4

CHAPTER 2 5

LITERATURE REVIEW 5

AN OVERVIEW OF WATER AND NUTRIENT MANAGEMENT IN POTATO-BASED ROTATION SYSTEMS 5

2.1 Introduction 5

2.2 The origin and importance of potato 5

2.2.1 Potato origin 5

2.2.2 Importance of potato 6

2.3 Potato water requirements and use efficiency 7

2.4 Potato nutrient management 8

2.4.1 Potato nutrient requirements 8

2.4.2 Potato nutrient removal and fertilizer input requirements 12

2.4.3 Fertilizer application methods for sustainable potato production 14

2.4.4 Nutrient use efficiency in potato production 16

2.4.5 Factors influencing nutrient use efficiency in potato production 19

2.5 Influence of potato-based rotation system on nutrient use efficiency 21

2.6 Conclusion 23

CHAPTER 3 24

TUBER YIELD AND WATER USE EFFICIENCY OF IRRIGATED POTATO PRODUCED ON SANDY SOILS 24

3.1 Introduction 24

3.2 Materials and methods 25

3.2.1 Study site description 25

3.2.2 Farm selection and crop management 26

3.2.3 Data collection and equipment installation 27

3.2.4 Weather data 28

3.2.5 Soil sampling 28

3.2.6 Yield analysis 29

3.2.7 Actual and potential irrigation need measurement 30

3.2.8 Drainage water sampling and analysis 31

3.2.9 Water use efficiency calculation 32

3.2.10 Estimation of drainage 33

3.3 Results and discussion 33

3.3.1 Weather during potato season 33

3.3.2 Fresh tuber yield and total dry matter production 35

3.3.3 Water use and use efficiency 37

3.3.3.1 Water inputs and evapotranspiration 37

3.3.3.2 Water use efficiency 41

3.3.4 Drainage water losses from potato fields 43

3.3.4.1 Comparison of estimated and measured drainage 45

3.4 Conclusions 46

CHAPTER 4 47

IN-FIELD MEASUREMENT OF NUTRIENT BALANCES AND NUTRIENT USE EFFICIENCY OF IRRIGATED POTATO GROWN ON SANDY SOILS 47

4.1 Introduction 47

4.2 Materials and methods 48

4.2.1 Soil sampling and analysis 48

4.2.2 Plant tissue sampling and nutrient analysis 49

4.2.3 Irrigation and drainage water nutrient analysis 49

4.2.4 Nutrient use efficiency calculation 50

4.2.5 Statistical analysis and potato production sustainability 50

4.3 Results and discussion 51

4.3.1 Potato nutrient input sources 51

4.3.1.1 Initial soil chemical properties before potato planting 51

4.3.1.2 Fertilizer type, rate and method of application 54

4.3.1.3 Irrigation water quality 55

4.3.1.4 Nutrient input levels from inorganic fertilizers and irrigation water 56

4.3.1.5 Correlation between total nutrient input rates and actual tuber yield 59

4.3.2 Potato nutrient outputs 60

4.3.2.1 Nutrient uptake and concentration in potato plant materials 60
4.3.2.2 Nutrient leaching loss from potato 62
4.3.2.3 Soil mineral concentration before planting and after potato harvest 64
4.3.2.4 Partial nutrient balance 68
4.3.3 Potato nutrient use efficiency 71
4.3.3.1 Partial factor productivity 71
4.3.3.2 Nutrient utilization efficiency 72
4.3.3.3 Nutrient harvest index 74
4.4 Conclusions 76
CHAPTER 5 78
EFFECT OF NUTRIENTS CARRIED-OVER AFTER POTATO HARVEST ON YIELD, WATER AND NUTRIENT USE EFFICIENCY OF SUBSEQUENT CROPS 78
5.1 Introduction 78
5.2 Materials and methods 79
5.2.1 Subsequent crop monitoring 79
5.2.2 Data collection and equipment installation 80
5.2.3 Weather data collection 80
5.2.4 Irrigation water quality, total water and nutrient input levels 80
5.2.5 Estimation of crop evapotranspiration 80
5.2.6 Soil sampling 81
5.2.7 Plant material sampling and nutrient analysis 81
5.2.8 Subsequent crop yield measurement 82
5.2.9 Drainage water sampling and nutrient analysis 82
5.2.10 Water and nutrient use efficiency of the subsequent crop 82
5.2.11 Overall potato - based rotation system partial nutrient balance 83
5.3 Results and discussion 84

5.3.1 Weather data 84

5.3.2 Water and nutrient inputs to the subsequent crops 85

5.3.3 Yield components, harvest index and water use efficiency of subsequent crops ……………………………………………………………………………93

5.3.4 Nutrient uptake and leaching 96

5.3.5 Nutrient use efficiency of subsequent crops 100

5.4 Conclusions 103

CHAPTER 6 105

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS 105

6.1 Summary of key findings and recommendations for farmers 108

6.2 Recommendations for future research..108

REFERENCES...110

APPENDIX...132

LIST OF FIGURES

Figure 3- 1: Location of each field near Louwna town, North West Province, South Africa. 26

Figure 3- 2: Centre-pivot quarter segments used in data collection. 28

Figure 3- 3: Ultrasonic flow meter (left) and pressure transducer with CR300 data logger (right) installed on a centre-pivot system. 30

Figure 3-4: Drainage lysimeter components (from Decagon Devices 2018). 32

Figure 3-5: Louwna daily maximum and minimum temperatures measured from October 2017 to February 2018 and August 2018 to December 2018 potato production seasons. 35

Figure 3-6: Actual and simulated potential fresh tuber yield obtained for each field. 36

Figure 3-7: Daily rain, irrigation, and evapotranspiration (ET), cumulative rain plus irrigation and cumulative ET for Field 1 (a), Field 2 (b) and Field 3 (c) applied to potato from planting to harvest. 39

Figure 3-8: Daily rain, irrigation, and evapotranspiration (ET), cumulative rain plus irrigation and cumulative ET for Field 4 (a), Field 5 (b) and Field 6 (c) applied to potato from planting to harvest. 40

Figure 3-9: Relationship between actual fresh tuber yield and actual irrigation amount (including values obtained for all fields). 43

Figure 3-10: Cumulative rain plus irrigation, cumulative evapotranspiration (ET) and cumulative drainage for Field 1. 44

Figure 4-1: Positive correlation between total phosphorous (P) input rate and fresh tuber yield for all fields. 60

Figure 4-2: Fortnightly and cumulative nutrient leaching events during the October 2017 to February 2018 potato growing season for Field 1. 63

Figure 4- 3: Soil profile initial soil available P (a), K (c), Ca (e) contents and final soil available P (b), K (d), and Ca (f) contents for the different fields before potato planting (initial) and after harvesting (final). 67

Figure 4- 4: Soil profile initial available Mg (a), initial soil mineral S (c) and final soil available Mg (b) and final soil mineral S (d) contents for the different fields before potato planting (initial) and after potato harvest (final). 68

Figure 4- 5: Nutrient harvest index (NHI) for potato as determined by tuber nutrient uptake at each Field. 75

Figure 5- 1: Subsequent crop water inputs through irrigation and rainfall for Field 1, 3, 4 and 5 recorded during the respective crop season. 86

Figure 5- 2: Daily rain, irrigation, crop evapotranspiration (ET_c), cumulative rain plus irrigation and cumulative ET_c for Field 3 (a), Field 4 (b) and Field 5 (c) applied to paprika, groundnuts and onion, respectively, from planting to harvest. 89

Figure 5- 3: Nutrient harvest index in economic harvestable products for paprika (Field 3), groundnuts (Field 4) and onion (Field 5). 98

Figure 5- 4: Nutrient harvest index in economic harvestable products for paprika fruits (Field 3), groundnuts grains (Field 4) and onion bulbs (Field 5). 101

LIST OF TABLES

Table 2-1: Water use efficiency (WUE), nutrient use efficiency of nitrogen (NUEN), total nitrogen (N) uptake in shoots and tubers and N recovery of potato applied with different water levels and 340 kg ha^{-1} N in west Nile Delta of Egypt (Badr et al. 2012). 8

Table 2-2: Recommended nutrient requirements of potato for target yield of between 45 – 56 t ha^{-1} (Stark et al. 2004, Alva et al. 2011). 13

Table 2-3: Recommended nutrient rates for potato with a yield potential of between 50 – 60 t ha^{-1} for a sandy loam soil (clay content of 10 – 20%) in South Africa. 13

Table 2-4: Nitrogen (N), phosphorus (P) and potassium (K) balance (kg ha^{-1}) in a potato-based rotation sequence of potato, spring wheat, sugar beet and oats (Vos and Van der Putten 2000). 22

Table 3-1: Field information regarding locality, cultivar type, and equipment installation, planting and harvesting dates. 27

Table 3-2: Soil bulk density, pH, cation exchange capacity (CEC), organic carbon content, and sand, silt and clay percentage of the different soil layers measured for each field before potato planting. 29

Table 3-3: Louwna daily average maximum and minimum temperature, daily average solar radiation, monthly average rainfall and grass reference evapotranspiration (ET_o) estimated during the potato production season from October 2017 to April 2019. 34

Table 3-4: Actual and potential tuber dry matter (DM) yield, actual aboveground DM yield, and yield gap ratio of actual to potential tuber DM yield of each field. 37

Table 3-5: Seasonal rainfall, observed irrigation amount, simulated irrigation requirement, estimated seasonal ET, water use efficiency based on rain and irrigation (WUE_{R+I}), potential water use efficiency (PWUE) and irrigation water use efficiency (IWUE) of potato production for all fields. 42

Table 3-6: Water inputs (rainfall and irrigation), water loss through evapotranspiration (ET), estimated and measured drainage for Fields 1, 3, 4 and 6. 46

Table 4-1: Soil pH, saturated paste electrical conductivity (EC_e), cation exchange capacity (CEC), available phosphorus (P), exchangeable potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) and sulphur (S) content (kg ha^{-1}) measured in different soil layers for each field before potato planting. 52

Table 4-2: Soil available phosphorus (P), exchangeable potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) and sulphur (S) content (mg kg^{-1}) measured in the top soil (0 – 0.3 m) layer for each field before potato planting. 53

Table 4-3: Fertilizer type, average observed and recommended application rates for potato production in Louwna area. 55

Table 4-4: The pH, electrical conductivity (EC), nitrate N (NO_3-N), hydrogen phosphate (H_2PO_4), potassium (K), calcium (Ca), magnesium (Mg), sulphate (SO_4) and sodium (Na) concentration of irrigation water used for potato production for each field. 56

Table 4-5: Nutrient input levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) from inorganic fertilizers and irrigation water applied for potato production for each field. 57

Table 4-6: Correlation between total nutrient input levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) and actual tuber yield of all potato fields. 59

Table 4-7: Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) uptake of tubers and aboveground potato parts for each field. 61

Table 4-8: Total drainage and nutrient leaching during the potato growing season of October 2017 to February 2018 for Field 1. 63

Table 4-9: Total nutrient inputs (A), nutrient exports (B) (tubers and in-season leaching) and partial nutrient balance (C) of potato for the intensively monitored fields (Fields 1, 3, 4 and 6). 69

Table 4-10: Partial factor productivity of N (PFPN), P (PFPP), K (PFPK), Ca (PFPCa), Mg (PFPMg) and S (PFPS) for each potato field as influenced by tuber yield and total nutrients applied. 72

Table 4-11: Nutrient utilization efficiency (NUtE) of nitrogen ($NUtE_N$), phosphorus ($NUtE_P$), potassium ($NUtE_K$), calcium ($NUtE_{Ca}$), magnesium ($NUtE_{Mg}$), sulphur ($NUtE_S$) as determined by potato total dry matter (DM) and nutrient uptake for each field. 73

Table 5- 1: Fallow period, crop type, planting and harvest dates of the subsequent crops planted after the potato crop for Fields 1, 3, 4 and 5. 80

Table 5-2: Crop coefficient values for the initial (Kc in), mid-season (Kc ms) and late-season (Kc ls) growth stages for paprika, groundnuts and onions (Allen et al. 1998). 81

Table 5-3: Length of crop development stages for paprika, groundnuts and onions (Estimated from values reported in Allen et al. 1998). 81

Table 5-4: Louwna daily average maximum and minimum temperature, daily average radiation, monthly total rainfall and monthly total reference evapotranspiration (ET_o) measured during the fallow period and during the subsequent crops season from March 2018 to April 2019. 85

Table 5-5: Irrigation water pH, electrical conductivity (EC), and mineral element concentration of ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), dihydrogen phosphate (H_2PO_4), potassium (K), calcium (Ca), magnesium (Mg), sulphate (SO_4), sodium (Na) and sodium adsorption ratio (SAR) for Field 3 (paprika), Field 4 (groundnuts) and Field 5 (onions). 90

Table 5-6: Soil pH, cation exchange capacity (CEC), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) content measured before subsequent crops planting for Fields 1, 3, 4 and 5. 91

Table 5-7: Nutrient input levels of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) from inorganic fertilizers, irrigation water and carried-over nutrients applied to paprika (Field 3), groundnuts (Field 4) and onions (Field 5) as subsequent crops grown after potato production in Louwna area. 92

Table 5-8: Paprika pepper yield components (leaf dry matter DM, stem DM, dry fruit yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for Field 3. 94

Table 5-9: Groundnuts yield components (total dry matter, dry pod yield, dry grain yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for Field 4. 95

Table 5-10: Onion yield components (aboveground biomass and bulb yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for both wet and dry samples. 96

Table 5-11: Nutrient uptake of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) for the different plant parts (leaves, stems and fruits/bulbs) of paprika (Field 3), groundnuts (Field 4) and onion (Field 5). 97

Table 5-12: Drainage amounts and leached nutrients of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) during the fallow and subsequent crop growth periods for Fields 1, 3 and 4 99

Table 5-13: Nutrient inputs (A) (kg ha^{-1}), nutrient exports (B) (kg ha^{-1}) and overall nutrient balance of potato-based rotation system (C) (kg ha^{-1}) for Fields 3 and 4. 103

LIST OF SYMBOLS AND ABBREVIATIONS

AE	Agronomic efficiency
Al	Aluminium
ARC	Agricultural Research Council
ARE	Apparent recovery efficiency
AWS	Automatic weather stations
B	Boron
C	Carbon
Ca	Calcium
$Ca(NO_3)_2$	Calcium nitrate
Ce	Nutrient concentration
CEC	Cation exchange capacity
D	Drainage
DCT	Divergence control tube
DL	Drainage lysimeter
DM	Dry matter
EC	Electrical conductivity
ET	Evapotranspiration
ETo	Reference surface evapotranspiration
Fe	Iron
HI	Harvest index
H	Hydrogen
ICP-OES	Inductively Coupled Plasma- Optical Emission Spectrometer
IWUE	Irrigation water use efficiency
K	Potassium
KNO_3	Potassium nitrate
Mg	Magnesium
$MgSO_4$	Magnesium sulphate
Mn	Manganese
N	Nitrogen
N_2O	Nitrous oxide
Na	Sodium
$(NH_4)_2SO_4$	Ammonium sulphate

NHI_{Ca}	Calcium harvest index
NHI_{K}	Potassium harvest index
NHI_{Mg}	Magnesium harvest index
NHI_{N}	Nitrogen harvest index
NHI_{P}	Phosphorus harvest index
NHI_{S}	Sulphur harvest index
NL	Nutrients leached
NO_2	Nitrogen dioxide
NO_3^-	Nitrate
NRE	Nutrient recovery efficiency
NS	Nutrient supplied
Nu	Nutrient uptake
NUE	Nutrient use efficiency
NUtE	Nutrient utilization efficiency
$NUtE_{Ca}$	Nutrient utilization efficiency of Ca
$NUtE_{K}$	Nutrient utilization efficiency of K
$NUtE_{Mg}$	Nutrient utilization efficiency of Mg
$NUtE_{N}$	Nutrient utilization efficiency of N
$NUtE_{P}$	Nutrient utilization efficiency of P
$NUtE_{S}$	Nutrient utilization efficiency of S
O	Oxygen
P	Phosphorous
PE	Physiological efficiency
PFP	Partial factor productivity
PFP_{Ca}	Partial factor productivity for Ca
PFP_{K}	Partial factor productivity for K
PFP_{Mg}	Partial factor productivity for Mg
PFP_{N}	Partial factor productivity for N
PFP_{P}	Partial factor productivity for P
PFP_{S}	Partial factor productivity for S
PNB	Partial nutrient balance
PNB_{Ca}	Partial nutrient balance for Ca
PNB_{K}	Partial nutrient balance for K

PNB_{Mg}	Partial nutrient balance for Mg
PNB_{N}	Partial nutrient balance for N
PNB_{P}	Partial nutrient balance for P
PNB_{S}	Partial nutrient balance for S
PWUE	Potential water use efficiency
S	Sulphur
SA	South Africa
SAS	Statistical Analysis System
SO_4^{2-}	Sulphate
SWB	Soil water balance
WUE	Water use efficiency
WUE_{R+I}	Water use efficiency based on rain plus irrigation
Zn	Zinc
$ZnSO_4$	Zinc sulphate

ABSTRACT

Water and nutrient management has a direct impact on yield, input-use efficiencies of crops, and is crucial to the ecological sustainability of production. Moreover, water-use efficiency (WUE) and nutrient-use efficiency (NUE) are common indicators of ecological sustainability in crop production. Measuring WUEs and NUEs of potato-based (*Solanum tuberosum* L.) rotation systems, rather than those of potato alone, provides a true image of water and nutrient use as well as the potential environmental pollution associated with potato production. Little is known, however, on the WUE and NUE of potato-based rotation systems within South Africa. This study was conducted to quantify WUE, NUE, drainage and nutrient leaching of potato fields, as well as to evaluate nutrient carry-over effects to the subsequent crop in rotation. Six irrigated potato fields on commercial farms in the North West province were selected for monitoring. Five of the six potato fields were monitored during the 2017/18 summer season, and one field during the 2018/19 season. After the potato season, follow-up crops of paprika (*Capsicum annuum* L.), groundnuts (*Arachis hypogaea* L.) and onions (*Allium cepa* L.) were monitored during the 2018/19 season in three fields. Surveys and field measurements were conducted regarding fertilizer type and application rate for both potato and follow-up crops. Flow meters and pressure transducers were used to monitor irrigation amounts. Drainage lysimeters were installed in four of the six fields to monitor drainage and nutrient leaching. Soil and plant samples were taken for nutrient analysis. Final yields of potato and the follow-up crops were determined at crop harvest. Calculated WUE was based on total water inputs from rainfall and irrigation (WUE_{R+I}), potential WUE (PWUE) was based on simulated tuber yield and evapotranspiration (ET), and irrigation WUE (IWUE) was based on observed irrigation. Nutrient-use efficiency was expressed as partial factor productivity (PFP), nutrient utilization efficiency (NUtE) and nutrient harvest index (NHI). Results revealed that average nutrient rates of 300 kg ha^{-1} N, 220 kg ha^{-1} P, 386 kg ha^{-1} K, 580 kg ha^{-1} Ca, 252 kg ha^{-1} Mg and 99 kg ha^{-1} S were applied to potato fields. Irrigation water applied to potato fields varied greatly and ranged from 590 – 1011 mm (average 866 mm) per season. Fresh tuber yields ranged from 60 – 93 t ha^{-1} (average 83 t ha^{-1}). Potato WUE_{R+I}, PWUE and IWUE ranged between 53 – 124, 96 – 151 and 59 – 129 kg mm^{-1}, respectively. Drainage of 488 mm was measured in one potato field and leaching of 29 kg ha^{-1} N, 20 kg ha^{-1} K, 484 kg ha^{-1} Ca, 179 kg ha^{-1} Mg and 129 kg ha^{-1} S was recorded. Partial factor productivity of N, P and K was quite similar for all potato fields, with average values of 288, 379 and 229 kg fresh tuber kg^{-1} of applied nutrient, respectively. A great variation in PFP among fields, however, was observed for Ca, Mg and S. Nutrient utilization efficiency and NHI of potato showed small field differences. Follow-up crop total input rates ranged between 140 – 328 kg ha^{-1} N, 108 – 284 kg ha^{-1} P, 171 – 406 kg ha^{-1} K, 1141 – 1232 kg ha^{-1} Ca, 405 – 944 kg ha^{-1} Mg and 165 – 216 kg ha^{-1} S. In follow-up crops, total water inputs ranged between 805 – 1526 mm (average of 1155 mm) per season. Paprika dry fruit yield of 5.5 t ha^{-1}, groundnut dry grain yield of 3.4 t ha^{-1} and onion fresh bulb yield of 75 t ha^{-1} were obtained. The WUE$_{R+I}$ for paprika, groundnuts, and onion were 3.6, 3.0 and 11.9 kg dry matter yield mm^{-1}, respectively. In conclusion, the growers achieved high potato yields, although substantial variability occurred between fields. Relatively high water and nutrient input rates were applied to potato and follow-up crops. However, these input rates were not necessarily proportional to crop yields achieved by the growers, which contributed to WUE and NUE variability among fields. The results revealed that the growers have room to improve WUEs and NUEs in potato and the follow-up crops, which can be achieved by using irrigation scheduling tools and adjust nutrient rates based on soil and irrigation water nutrient status.

Keywords: drainage, harvest index, follow-up crops, leaching, partial factor productivity, tuber yield

CHAPTER 1

GENERAL INTRODUCTION

Ecological sustainability in relation to food production means ensuring food availability for the growing human population while conserving natural resources for future generations (Tilman et al. 2002, Haverkort et al. 2009). Climate change, land degradation, water scarcity and limited access to agricultural inputs, however, remain a major threat to sustainable agricultural production (Kassam and Friedrich 2012, Drechsel et al. 2015). It is estimated that the world population will reach 8.5 billion by 2030 and 9.7 billion people by the year 2050 (UN DESA 2015). In order to provide food to the increasing population, agricultural output must increase through either crop production intensification on land already under cultivation, or production expansion on new land (Drechsel et al. 2015, Svubure et al. 2015).

Further yield increase through production area expansion seems difficult to achieve especially in regions where most of the arable land is already under agriculture or used for human settlement (Tilman et al. 2002). This implies that production area expansion can only take place on marginal lands that are unlikely to produce the desired crop yields, in addition to causing major environmental problems such as increased greenhouse gases, pollution, biodiversity loss and land degradation (Tilman et al. 2002, Garnett et al. 2013). Therefore, yield increase on already existing farmlands through intensive crop production remains the most viable option (Svubure et al. 2015). Yet intensive crop production for high yields requires large amounts of agriculture inputs of fertilizers, water, pesticides and seeds (Tilman et al. 2002, Svubure et al. 2015, Steyn et al. 2016).

Sustainable maintenance of high yields on the same piece of land necessitates an efficient use of agricultural inputs. Efficient use of farm inputs refers to the amount crop yield produced per unit of resource input applied (Baligar et al. 2001, Baligar and Fageria 2015, Svubure et al. 2015, Steyn et al. 2016). Nutrient use efficiency (NUE) and water use efficiency (WUE) are vital indicators of economically and ecologically sustainable crop production as well as being important in evaluating the productivity of cropping systems (Van Ittersum and Rabbinge 1997, De Vries et al. 2010, Fixen et al. 2015, Steyn et al. 2016).

Nutrient use efficiency presents a useful measure of crop fertilizer or nutrient recovery from the soil (Dobermann 2007, Fixen et al. 2015). As the cost of chemical fertilizers is rising, there is a need to increase NUE of cropping systems for both economic and ecological sustainability

(Steyn et al. 2016). Attaining high NUE and WUE helps to minimize water and nutrient losses from the field, which contributes to overall cropping system productivity and sustainability (Mikkelsen et al. 2012). Nonetheless, WUE and NUE of potato cropping systems are greatly influenced by factors such as water and fertilizer management, cultivar type, soil and weather conditions (Baligar et al. 2001, Fageria et al. 2008, Fixen et al. 2015). Therefore, achieving increased WUE and NUE requires a careful balance between the various crop production practices such as water and nutrient management, weeds, pest and disease control, and use of improved crop cultivars (Kassam and Friedrich 2012).

Potato (*Solanum tuberosum* L.) is one of the most important non-cereal crops with the potential to provide food security to households in many parts of the world (Birch et al. 2012, Haverkort and Struik 2015, George et al. 2018). The average world production reported for 2016 was 376 million tons of fresh tubers harvested from approximately 19.2 million hectares (FAOSTAT 2017). Asia and Europe together account for more than 81% of the world´s production. Specifically, China and India contribute a third of the potato harvested yield (FAOSTAT 2017). Africa contributes 0.06% of the word´s potato production, with Egypt as the top producer accounting for 20%, followed by Algeria with 19.5% and South Africa (SA) with 9.0% of the Africa´s total production (FAOSTAT 2017). Other African countries with high potato production include Tanzania, Morocco, Kenya, Nigeria and Malawi.

Potato production in SA has increased over the years, arising from expansion of the growing area, establishment of high yielding cultivars and improved production practices (Potatoes South Africa 2016). In addition to this, there has been an increase in the per capita consumption of potatoes in SA from 32 kg to 40 kg per annum from 2005 to 2016 (Potatoes South Africa 2016). Haverkort (1990) stated that increase in potato consumption can be attributed to the relative ease of cultivation and high nutritional content of the tubers. Potatoes contain easily digestible carbohydrates, fibres, minerals and vitamins (Nieto 2016). For this reason, potato has been identified as an important crop in providing food security and income to households in SA (Steyn et al. 2016). The major potato producing regions in SA include Limpopo, the Eastern Free State, Sandveld and the Western Free State (Potatoes South Africa 2016). However, the crop is also grown in other parts of the country on a small scale.

Potato production has increased mainly due to its adaptability to various climatic conditions, high yielding potential and relatively short production cycle (Haverkort 1990, Alva et al. 2011). The crop takes up relatively large amounts of nitrogen (N) and potassium (K), while phosphorous (P), calcium (Ca), magnesium (Mg), sulphur (S), zinc (Zn), iron (Fe) manganese (Mn) and boron (B) are generally required in smaller amounts (Dean 1994, Munoz et al. 2005, Westermann 2005, Alva et al. 2011, Steyn et al. 2016).

Generally, fertilizer recoveries of 40 – 65% N, 15 – 25% P and 30 – 50% K have been observed for experimental research plots of various crops in the first year of application (Delgado et al. 2001, Drechsel et al. 2015). Potato fertilizer recovery efficiency is likely to be even lower than the reported first year recovery efficiencies of most crops, since the crop has a relatively shallow root system (Webb et al. 2000, Munoz et al. 2005, Prasad et al. 2015). Nevertheless, unrecovered nutrients by potato are not necessarily lost from the soil system (Aguilera et al. 2014). Unrecovered nutrients by potato as well as those lost to deeper soil layers through drainage and leaching, can be recovered by a relatively deep-rooted crop such as maize (*Zea mays* L.) planted in rotation after potato (Delgado et al. 2001, Munoz et al. 2005, Aguilera et al. 2014).

Potato-based rotation systems can increase WUE and NUE in potato fields, with additional benefit of reduced pollution to the environment (Munoz et al. 2005, Swain et al. 2014). Increasing WUE and NUE of potato cropping systems using crop rotation, however, depend on the follow-up crop management and the complementary outcome of fertilizer management based on applying the right fertilizer type, in the correct amount as required by the plant, placed in the right place at the right time of plant growth (IFA 2009, Drechsel et al. 2015).

However, detailed measurements of water and nutrient dynamics in potato-based rotations have not been investigated in SA. For that reason, this study was aimed at conducting field studies to monitor water and nutrient application rates, drainage and nutrient leaching from potato fields. In addition, the study aimed at quantifying the amount of soil-applied nutrients left after potato harvest and their effect on yield production of a follow-up crop planted in rotation.

1.1 Problem statement

Water and nutrient management has a direct impact on yield of potato, and is key to sustainable potato production. Detailed measurements of WUE and NUE in potato-based rotations are not available in SA. A study by Steyn et al. (2016) identified major differences in resource use efficiencies of potato among growers in the 16 main growing regions of SA. However, the information obtained in the survey of this study did not outline the exact reasons for the large within region variability of WUEs and NUEs, since detailed measurements of soil and weather characteristics, input application and other crop management strategies were lacking. In addition, the effect of nutrients carried-over from potato to a subsequent crop was not studied. Therefore, this study was aimed at conducting field studies to monitor water and nutrient application rates, drainage and nutrient leaching from potato fields. In addition, the study aimed at quantifying the amount of soil-applied nutrients left after potato harvest and their effect on yield production of a follow-up crop planted in rotation. North West region was selected for this study because it was identified as one of the potatoes growing regions with low WUE and NUE (Steyn et al. 2016). Explaining the variability in WUE and NUE among fields is important to identify the success factors that make some potato growers highly efficient and more sustainable than others. Information obtained from this study is crucial in identifying water and nutrient management strategies to be implemented for sustainable potato production.

1.2 Hypotheses

I. Drainage and leaching is high in potato grown on sandy soils.
II. Water and nutrient use efficiencies differences among potato fields are mainly due to differences in drainage and leaching during the crop season.
III. Carry-over nutrients from potato fields will be available for the subsequent crop uptake.

1.3 Objectives

I. Assess nutrient application rates and yields in potato and in the subsequent crop in rotation through surveys and field measurements in a selected number of fields in the North West Province of SA.
II. Quantify drainage and leaching from potato fields of North West.
III. Evaluate nutrient carry-over effects from potato to the subsequent crop yield production.
IV. Determine the variability in WUE and NUE of potato fields and explore management practices that can be adopted to reduce water and nutrient losses.

CHAPTER 2

LITERATURE REVIEW

AN OVERVIEW OF WATER AND NUTRIENT MANAGEMENT IN POTATO-BASED ROTATION SYSTEMS

2.1 Introduction

Water and nutrient management is important in potato (*Solanum tuberosum* L.) production for high yield, as well as minimizing nutrient losses to the environment (Badr et al. 2012, Sun et al. 2015). Adequate water supply to potato is critical to avoid water stress which could result in low marketable yield (Steyn et al. 1998). Excessive water application in potato can cause yield losses due to tuber rot and also increases the risk for nutrient leaching beyond the potato rooting zone (Munoz et al. 2005). Therefore, water application rate should be determined based on seasonal potato crop water requirements to increase tuber yield produced per unit of water applied, which is also known as water use efficiency (WUE) (Badr et al. 2012).

Optimum nutrient supply in potato is important for adequate crop growth and increased tuber yield per unit of nutrients applied, which is referred to as nutrient use efficiency (NUE) (Westermann 2005, Alva et al. 2011). Insufficient nutrient supply leads to reduced potato crop growth, which results in low yield and NUE. Excess nutrient supply results into increased vegetative growth at the expense of tuber dry matter accumulation as well as an increased risk for nutrient loss to the environment, mainly through leaching (Munoz et al. 2005). Therefore, water and nutrient optimization in potato is essential for sustainable crop production.

2.2 The origin and importance of potato

2.2.1 Potato origin

Potato originated from South America in the Andes Mountains of the present day southern Peru and northern Bolivia (Hawkes and Francisco-Ortega 1993, Hijmans and Spooner 2001). The native people of the region domesticated wild potato species for food and medicinal uses during the early 1500s (Hawkes and Francisco-Ortega 1993). For this reason, Peru possesses the highest number of wild potato species (Hijmans and Spooner 2001). Presently, the commonly cultivated potatoes originated from across the highlands of eastern Venezuela to northern

Argentina, and others from the lowlands of Chile (Ames and Spooner 2008, Machida-Hirano 2015). Potatoes were later exported to the Canary Islands, Europe and to the rest of the world (Hawkes and Francisco-Ortega 1993, Ríos et al. 2007).

Cultivated potatoes are classified into a single species of *Solanum tuberosum* L., which has eight cultivar groups that include Ajanhuiri, Andigenum, Chaucha, Chilotomum, Curtilobum, Juzepczukii, Phureja and Stenotomum (Ríos et al. 2007). Due to hybridization and breeding, numerous potato varieties have been developed and adapted to various altitudes, latitudes and photoperiods as well as to different soil conditions (Haverkort 1990, Alva et al. 2011, Machida-Hirano 2015). The great extent of potato adaptation to different climatic zones has facilitated potato production all year round, in the tropical and subtropical high- and lowlands, and also in temperate regions (Haverkort 1990, Alva et al. 2011).

2.2.2 Importance of potato

Potato ranks fourth as the most important crop after maize, rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) in terms of production (Alva et al. 2011, Steyn et al. 2016), and is ranked as the third most important food crop after rice and wheat (Birch et al. 2012, Haverkort and Struik 2015, George et al. 2018). Potato has emerged as an important source of food and nutrition security to people in many countries (Birch et al. 2012, George et al. 2018). Birch et al. (2012) documented that more than a billion people eat potato, which provides proteins, minerals, vitamins and carbohydrates to the body.

Potato production has increased due to high demand for food, as animal feed and industrial use in many countries (Birch et al. 2012). The average world production reported for 2016 was 376 million tons of fresh tubers harvested from approximately 19.2 million hectares, resulting in an average yield of approximately 19.5 t ha^{-1} (FAOSTAT 2017). The relatively high potato yield per unit area is explained by the fact that potato allocates a range of 75 – 92% of the accumulated dry matter to harvestable tubers (Vos 1997, Belanger et al. 2001, Mazurczyk et al. 2009), as compared to 30 – 60% of the total accumulated dry matter allocated to harvestable grains of cereals in general (Hay 1995). This indicates that potato has the potential to address hunger and nutrition problems facing many countries, especially in Africa and Asia (Haverkort and Struik 2015, George et al. 2018). Sustaining potato productivity at high levels, however, requires good knowledge of crop water and nutrient requirements (Westermann 2005, Alva et al. 2011).

2.3 Potato water requirements and use efficiency

Potato has a high water demand and is sensitive to water stress, particularly during tuber bulking stage (Steyn et al. 1998, Shock et al. 2007, Badr et al. 2012, Sun et al. 2015). Seasonal water requirements for potato range from 300 – 850 mm, depending on the weather conditions, cultivar and the length of the growing season (Panigrahi et al. 2001, Vos and MacKerron 2006, Shock et al. 2007, Carli et al. 2014). However, water inputs in excess of 900 mm are applied to potato grown in dry areas and during summer seasons when the evaporative demand is high (Carli et al. 2014). Frequent water addition is required to maintain optimum soil water levels, especially for potato grown on medium- to coarse- textured soils (Begum et al. 2018).

Water management in potato production is imperative to avoid both under- and over-irrigation (Steyn et al. 1998, Shock et al. 2007). Under-irrigation leads to reduced plant growth, poor tuber set and increased misshapen tubers, which collectively lower marketable tuber yield (Shock et al. 2007). Low soil water content during tuber initiation stage may lead to reduced number of tubers and defects such as dumbbell-shape and internal brown spot of tubers (Abbas and Ranjan 2015). Additionally, water stress limits potato root growth, which affects nutrient acquisition from the soil (Liu et al. 2006, Ahmadi et al. 2011). Reduced plant growth can also lead to inefficient use of applied nutrients, resulting in low NUE. Over-irrigation in potato can lead to root and tuber rot, increased disease incidence, runoff, drainage and nutrient leaching, thereby reducing tuber yield, WUE and NUE (Waddell et al. 2000, Munoz et al. 2005, Shock et al. 2007). Adequate soil water content permits mass flow of nutrients to the roots, which increase plant nutrient uptake, growth and marketable yield (Drechsel et al. 2015). Furthermore, maintenance of sufficient soil water content increases soil organic matter and chemical fertilizer mineralization rates, which improve mineral phyto-availability of nutrients for potato absorption (Drechsel et al. 2015, Sun et al. 2015).

Water supply through irrigation is required for potato production, especially in areas that receive low and irregular rainfall (Liu et al. 2006, Badr et al. 2012, Sun et al. 2015). The most commonly used irrigation systems in potato production include furrow, sprinkler and center-pivot systems (Munoz et al. 2005). Water management through application regimes such as full, deficit and partial root-zone drying irrigation may be adapted to potato cropping systems, depending on water availability, soil and weather conditions of the area (Liu et al. 2006, Badr et al. 2012, Sun et al. 2015). Irrigation application regimes that optimize water use without causing a reduction in tuber yield also lead to increased WUE, nutrient recovery and NUE

(Table 2-1) (Badr et al. 2012). Therefore, the choice of an appropriate irrigation system and application regime is critical for both maintaining adequate soil water content and optimizing potato WUE and NUE (Table 2-1) (Waddell et al. 2000, Shock et al. 2007).

Table 2-1: Water use efficiency (WUE), nutrient use efficiency of nitrogen (NUE_N), total nitrogen (N) uptake in shoots and tubers and N recovery of potato applied with different water levels and 340 kg ha^{-1} N in west Nile Delta of Egypt (Badr et al. 2012).

Irrigation water regime (% of crop ET)	WUE (kg ha^{-1} mm^{-1})	NUE_N (kg yield kg^{-1} N)	N uptake (kg ha^{-1})	N Recovery (%)
100	146	136	210	58
80	170	127	194	53
60	159	88	139	37
40	154	55	102	26
LSD 5%	5.91	5.85	4.28	-

LSD (5%): least significant deference at 5% probability level
Crop ET: crop evapotranspiration (328 mm)

2.4 Potato nutrient management

Nutrient management and supply in any cropping system requires knowledge of the crop nutrient requirements while taking into consideration of the target yield level, soil inherent fertility and the prevailing weather conditions (Westermann 2005, Alva et al. 2011).

2.4.1 Potato nutrient requirements

The macro- and micro-nutrients required by potato are either essential or beneficial to the plant (Taiz and Zeiger 2002, Westermann 2005). The essential and beneficial nutrients are directly involved in the formation of plant structures and other metabolic processes required to complete its life cycle (Taiz and Zeiger 2002, Westermann 2005, Jones 2012). Apart from carbon (C), hydrogen (H) and oxygen (O) that are obtained from air and water, the plant should obtain the following essential nutrients from soil and fertilizer sources: nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), sulphur (S), magnesium (Mg), zinc (Zn), manganese (Mn), iron (Fe), boron (B), copper (Cu), molybdenum (Mo) and chlorine (Cl) (Taiz and Zeiger 2002, Stark et al. 2004, Westermann 2005, Jones 2012, Kaur et al. 2017). The most limiting nutrients for potato growth are N, P, K, Ca, Mg and S and their importance is briefly discussed in the following section.

2.4.1.1 Nitrogen

Nitrogen is usually the first limiting nutrient in potato production, affecting all growth stages (Dean 1994, Govindakrishnan and Haverkort 2006, Zebarth and Rosen 2007, Alva et al. 2011, Banerjee et al. 2016). Nitrogen is important in many physiological and morphological processes of the potato plant such as leaf appearance and early canopy development, which attributes are central for maximum light interception and photosynthesis (Govindakrishnan and Haverkort 2006, Zebarth and Rosen 2007, Alva et al. 2011). Nitrogen application is essential for proper tuber growth and development as it influences tuber initiation and bulking stages (Love et al. 2005, Alva et al. 2011, Banerjee et al. 2016, Hailu et al. 2017). Various studies have revealed that N application increases marketable potato tuber yield (Belanger et al. 2001, Miller and Rosen 2005, Zebarth and Rosen 2007, Banerjee et al. 2016).

Potato is highly sensitive to both N deficiencies and excesses (Alva et al. 2011). Insufficient N supply results in reduced vegetative growth, which affects light interception and photosynthesis (Alva et al. 2011, Banerjee et al. 2016). Low N levels also lead to early crop senescence, poor tuber development and low yield (Love et al. 2005, Alva et al. 2011). Excessive N leads to delayed tuber onset, and promotes more stem and leaf growth at the expense of tuber growth (Love et al. 2005, Govindakrishnan and Haverkort 2006, Alva et al. 2011). Sharma and Arora (1987) reported a negative response of yield decrease with increase in N application rate from 200 – 250 kg ha^{-1}. Similarly, Zebarth et al. (2004a, b) reported a decrease in tuber yield and N harvest index with increasing N supply to the potato crop.

Excessive N application rates also negatively affect both the economic and ecological sustainability of potato production system (Alva et al. 2011, Prasad et al. 2015). The NUE of N in potato is about 50% in most of the production areas (Govindakrishnan and Haverkort 2006, Rens et al. 2018). This implies that about 50% of the applied N fertilizer is liable to losses through leaching, runoff, volatilization, denitrification and immobilization processes (Shaviv and Mikkelsen 1993, Davenport et al. 2005, Alva et al. 2011, Jiang et al. 2012). Leaching and runoff of nitrate (NO_3^-) are the major non-point sources of fresh water contamination (Westermann 2005, Prasad et al. 2015), while denitrification leads to release of N oxides that contribute to the greenhouse effect (Davenport et al. 2005, Prasad et al. 2015). For this reason, proper N management is required for increased use efficiency and to achieve sustainable potato production.

2.4.1.2 Phosphorus

Phosphorus is commonly the second most limiting mineral nutrient in potato production (Alva et al. 2011, Banerjee et al. 2016). Potato has a high P requirement (Alva et al. 2011, Rosen et al. 2014, Banerjee et al. 2016), and the crop is inefficient in taking up P from the soil. Accordingly, adequate P supply is vital for early root growth, plant height and leaf area expansion of potato (Alva et al. 2011, Rosen et al. 2014, Banerjee et al. 2016). Phosphorus also influences tuber yield, due to its effect on tuber number and size distribution. Increased P levels reduce larger sized tubers while increasing small to medium sized tubers (Hanley et al. 1965, Sharma and Arora 1987, Govindakrishnan and Haverkort 2006). Sharma and Arora (1987) reported a positive response on tuber yield to increasing P fertilizer levels through an increase in the weight of tubers within the small and medium grades (Sharma and Arora 1987). Insufficient P supply affects early root growth and canopy development, which reduce plant growth and yield.

2.4.1.3 Potassium

Potassium improves potato growth through promoting plant height, canopy development and dry matter accumulation (Taiz and Zeiger 2002, Alva et al. 2011, Banerjee et al. 2016). In addition, K fertilizer application increases yield, size distribution and tuber specific gravity (Sharma and Arora 1987, Banerjee et al. 2016). Sharma and Arora (1987) reported that application of K increases the number of tubers in the medium and large size grades at the expense of smaller sized tubers. Potassium also participates in carbohydrates remobilization from stems and leaves to the tuber, which increases tuber starch content (Westermann et al. 1994). Adequate K facilitates plant water uptake, thereby increasing WUE of potato (Taiz and Zeiger 2002). However, the presence of excess K in soil leads to luxury uptake and translocation of K in large amounts to the tubers, which increases tuber water absorption and the subsequent reduction in tuber specific gravity (Stark et al. 2004). Hence, it is important for potato growers to ensure optimal K supply in order to obtain high quality tuber yield.

2.4.1.4 Calcium

Calcium is important in strengthening plant cell membrane and cell wall structures, which confers maximum tissue resistance to mechanical injury and pest and disease damage (Taiz and Zeiger 2002, Gunter and Palta 2008, Jones 2012). This implies that inadequate Ca supply to any plant tissue renders that specific organ susceptible to mechanical damage and attack by pathogens (Gunter and Palta 2008). Absorbed Ca by the plant roots is transported with moving water in the xylem due to transpiration, leading to high Ca accumulation in the foliage (Taiz and Zeiger 2002, White and Broadley 2003, Gunter and Palta 2008). This may cause Ca deficiency in roots and tubers at low transpiration rate (Palta 1996, Ozgen et al. 2006, Gunter and Palta 2008). Moreover, Ca is not re-translocated in the plant, so tuber deficiencies are possible, even if the foliage has enough Ca. Potato tubers deficient in Ca usually experience physiological disorders such as internal brown spot and hollow heart (Palta 1996, Stark et al. 2004, Ozgen et al. 2006, Gunter and Palta 2008). These disorders reduce tuber quality and marketability, which lower the profit margin. Therefore, Ca fertilizer application is usually necessary to supplement soil exchangeable Ca supply (Stark et al. 2004, Gunter and Palta 2008). Previous research showed that stolons and functional roots on the tubers efficiently absorb soil applied Ca (Kleinhenz et al. 1999, Ozgen et al. 2006, Gunter and Palta 2008). Gunter and Palta (2008) reported that in-season application of 168 kg Ca ha^{-1} in soils with exchangeable Ca ranging from 285 – 563 mg kg^{-1} significantly increased tuber tissue Ca concentration. Hence, in-season Ca fertilizer application should coincide with the tuber bulking stage for increased tuber Ca concentration (Kleinhenz et al. 1999, Ozgen et al. 2003, 2006, Gunter and Palta 2008).

2.4.1.5 Magnesium

Magnesium participates in numerous physiological and biochemical processes that are directly linked to plant growth and development (Jones 2012). Magnesium forms part of the chlorophyll molecule that is responsible for light energy absorption during photosynthesis (Taiz and Zeiger 2002, Westermann 2005, Gerendás and Führs 2013, Senbayram et al. 2015). In root and tuber crops, Mg is involved in the translocation and partitioning of photosynthetic assimilates, which increase harvestable root and tuber starch content (Feltran et al. 2004, Gerendás and Führs 2013, Senbayram et al. 2015). Magnesium also improves tuber firmness and resistance against mechanical damage (Gerendás and Führs 2013). Poberezny and Wszelaczyñska (2011) reported that Mg application at 100 kg ha^{-1} effectively lead to increased tuber dry matter and starch content. Based on Mg functions in potato growth and development, insufficient supply of this nutrient directly impairs remobilization of the photosynthesis assimilates from the leaves and haulms to developing tubers, which may reduce tuber quality and yield (Taiz and Zeiger 2002, Gerendás and Führs 2013).

2.4.1.6 Sulphur

Sulphur is involved in various physiological and biochemical reactions in plant cells (Jones 2012, Singh et al. 2016). In potato production, S application in deficient soils has been observed to increase plant dry matter (DM) accumulation and tuber yield (Trehan et al. 2008a, Sharma et al. 2011, Singh et al. 2016). Additionally, adequate S supply improves N, P, and K nutrient recovery and micronutrient availability to potato (Sharma et al. 2011, Klikocka et al. 2015, Singh et al. 2016). Singh et al. (2016) reported that combined application of N and S at a rate of 180 kg ha^{-1} and 50 kg ha^{-1}, respectively, significantly enhanced plant DM accumulation and tuber yield. This results in high tuber quality and yield, as well as increased overall NUE (Sharma et al. 2011). Hence, S addition through fertilizer application is required in potato production.

2.4.2 Potato nutrient removal and fertilizer input requirements

In order to achieve desired tuber size and marketable yield, high fertilizer input rates are required (Zebarth and Rosen 2007, Jiang et al. 2012, Banerjee et al. 2016). Trehan et al. (2009) stated that potato removes large amounts of nutrients per unit area since it has a fast growth rate during the early stages. Nutrient recommendation for potato is based on whole plant nutrient removal for a specific target tuber yield. Westermann (2005) documented that potato with a target yield of 56 t ha^{-1} takes up 235 kg ha^{-1} N, 31 kg ha^{-1} P, 336 kg ha^{-1} K, 91 kg ha^{-1} Ca, 63 kg ha^{-1} Mg and 22 kg ha^{-1}of S. The recommended nutrient requirements for potato in Idaho based on nutrient uptake for a target yield of between 45 – 56 t ha^{-1} is presented in Table 2-2 (Stark et al. 2004, Alva et al. 2011). Fertilizer guidelines for potato production in South Africa (SA) are based on yield potential, soil type and the soil analysis (Steyn and Du Plessis 2012). For example, the N, P and K recommendations for a yield potential of between 50 – 60 t ha^{-1} for a sandy loam soil (clay content of 10 – 20%) in SA is presented in Table 2-3.

Table 2-2: Recommended nutrient requirements of potato for target yield of between 45 – 56 t ha^{-1} (Stark et al. 2004, Alva et al. 2011).

Nutrient	Nutrient uptake ranges (kg ha^{-1})
Nitrogen (N)	225 – 270
Phosphorus (P)	28 – 40
Potassium (K)	310 – 360
Calcium (Ca)	56
Magnesium (Mg)	45
Sulphur (S)	20 – 30

Table 2-3: Recommended nutrient rates for potato with a yield potential of between 50 – 60 t ha^{-1} for a sandy loam soil (clay content of 10 – 20%) in South Africa (Steyn and Du Plessis 2012).

Nutrient	Recommended rates (kg ha^{-1})
Nitrogen (N)	220 - 240
Phosphorous (P)[a]	70 - 80
Potassium (K)[b]	230 - 260

[a] Recommended for soils with available P of between 25 – 30 mg kg^{-1} (P-Bray 1).
[b] Recommended for soils with cation exchange capacity (CEC) of greater than 6 $cmol_c$ kg^{-1} when the quantity of K is less than 4% of the CEC.

The application rates of nutrients are generally site-specific and mainly influenced by soil type and fertility, potato cultivar and target yield (Stark et al. 2004, Zebarth and Rosen 2007). Furthermore, fertilizer application rates are restricted by law in most of the countries in order to minimize excessive application that usually results into environmental pollution. The average fertilizer application rates within potato producing regions of SA range from 132 – 373 kg ha^{-1} N, 36 – 169 kg ha^{-1} P and 96 – 510 kg ha^{-1} K (Steyn et al. 2016), depending on the soil type, soil nutrient status and target yield. Similarly, Sparrow (2012) reported that N, P and K median application rates greater than 200 kg ha^{-1} N, 200 kg ha^{-1} P and 300 kg ha^{-1} K are used in potato producing regions of Tasmania, Australia. The recommended N rate in New Brunswick in Canada ranges from 165 – 185 kg ha^{-1} (Zebarth et al. 2004a), while the economic optimal N application rate used in northwestern Europe ranges from 150 – 250 kg ha^{-1} (Vos 2009).

It is clear that a large variation exists in fertilizer application rates in the different potato production regions of the world. Sparrow (2012) mentioned that potato growers tend to use high rates of N, P, and K on responsive sites, based on a notation that the yield benefits outweigh the potential nutrient loss risks. Likewise, high N, P, and K application rates are generally used in potato produced on sandy soils where nutrient loss risk through leaching is high (Steyn et al. 2016). Soils that have a high fertilizer P fixation and retention capacity may require high application rate of this specific nutrient in order to meet the crop growth requirements (Westermann 2005, Sparrow 2012). For instance, fertilizer rates between 131 – 196 kg ha^{-1} P are used for potato production in the southern part of Chile that has volcanic soils with a high P retention capacity (Haverkort et al. 2014).

2.4.3 Fertilizer application methods for sustainable potato production

The effectiveness of fertilizers to meet nutrient requirement levels for sustainable potato production largely depend on the rate, method of application, fertilizer source and the timing of application during a specific crop development stage (IFA 2009, Jones 2012, Drechsel et al. 2015, Rens et al. 2018). Various ways of applying fertilizers exist to obtain optimum use efficiency and maximum potato yields (Westermann 2005). Nutrient timing and application methods commonly employed in potato production include pre-plant broadcasting, band placement in rows at planting, top- and side-dressing after planting, foliar application during the vegetative stage, and fertigation (Westermann 1993, Stark et al. 2004, Westermann 2005).

2.4.3.1 Broadcasting

Broadcasting consists of fertilizer application to the soil surface (Westermann 1993, Jones and Jacobsen 2009). It is the most extensively used fertilizer application method in potato mainly because of machinery availability and low cost as compared to banding and foliar application methods (Jones and Jacobsen 2009, Ekelöf 2014). Incorporating and mixing of fertilizers into the soil greatly improves broadcasting effectiveness, which increase fertilizer soil contact area and its adsorption rate (Ekelöf 2014). This may promote better root distribution and encourage early canopy closure for increased light interception and photosynthesis (Thomason et al. 2015). Pre-plant broadcast and incorporation of soil immobile fertilizers such as P increase root contact and plant growth (Jones and Jacobsen 2009). Westermann (2005), Jones and Jacobsen (2009) documented that top dressing with both granular and liquid fertilizers before row closure can be effectively done through broadcasting. Nonetheless, broadcast is the least effective fertilizer application method in terms of delivering the applied nutrients for plant uptake and requires a larger amount of fertilizer inputs compared with other methods (Ekelöf 2014). This is because the shallow and sparse potato roots cannot effectively reach fertilizers applied in furrows (Zebarth et al. 2012). In addition, furrows tend to have a high infiltration rate, which increases leaching of broadcasted fertilizers (Zebarth et al. 2012). Therefore, knowledge of mobility and availability of applied nutrients is required when adopting the broadcast fertilizer application method.

2.4.3.2 Banding

Banding is a localized fertilizer placement method, which involves fertilizer application in a continuous strip on potato hills parallel and close to the crops (Westermann 1993, Ekelöf 2014). Banding places fertilizers in the root zone where nutrients can be accessed easily and absorbed, which increases nutrient uptake, especially during the early crop growth stages (Westermann and Sojka 1996, Zebarth et al. 2012, Ekelöf 2014). Fertilizer bands are placed close enough to potato seed piece to promote early growth and canopy closure (Westermann 1993). Also, the fertilizer band placed on potato hills maintains a high nutrient concentration, which supplies adequate nutrient amounts to the plant (Zebarth and Milburn 2003). Rahman et al. (2004) reported a substantial increase in marketable tuber yield with banded application of N, P, and K as opposed to broadcasting. Similarly, Khan et al. (2007) found out that tuber size, number of tubers and tuber yield increased significantly when N fertilizers were applied through banding, compared with broadcast. In their experiment, the authors concluded that banding is a more efficient fertilizer application method in potato as compared to broadcasting (Khan et al. 2007).

2.4.3.3 Foliar application

Foliar application involves spraying of fertilizer solution onto plant leaves (Westermann 1993, Taiz and Zeiger 2002, Velu et al. 2014). Nutrient elements in the solution are readily absorbed through the leaf cuticle and stomata, and thereafter translocated to various plant parts (Taiz and Zeiger 2002, Cakmak 2008, White and Broadley 2009). Foliar nutrient spray can be effective in treating nutrient deficiencies in potato and usually produce quicker response than soil applied nutrients (Westermann 1993, Stark et al. 2004). According to Westermann (2005), foliar spray can successfully correct foliar deficiencies, but is less effective in correcting tuber nutritional problems for phloem immobile nutrients, such as Ca. Moreover, the amount of nutrients applied directly to the leaves is limited, as high salt concentrations might cause leaf burn (Westermann 1993, Taiz and Zeiger 2002, Stark et al. 2004). Therefore, this method is more suited in application of micro-nutrients such as Zn, Mn, Cu, Fe and B, which are required in relatively smaller amounts by the plant as opposed to macro-nutrients (Taiz and Zeiger 2002, Stark et al. 2004, Westermann 2005). Nevertheless, foliar fertilizer application can be used to supplement most macro- and micro-nutrients in potato (Stark et al. 2004, Westermann 2005).

2.4.3.4 Fertigation

Fertigation involves simultaneous water and nutrient supply to crops in irrigation water (Westermann 1993, Westermann 2005, Mikkelsen et al. 2015). Soluble nutrient sources are suited for this method of application, compared to less-soluble sources (Westermann 1993, Westermann 2005, Mikkelsen et al. 2015). Fertigation allows adjustment of the nutrient application rate in order to meet crop nutritional needs (Bar-Tal et al. 2015). Water and nutrients are applied at the correct time and in close proximity to plant roots, which can improve crop growth, tuber yield and NUE (Westermann 1993, Westermann 2005). Furthermore, multiple fertilizer applications are possible with fertigation during the season, thereby reducing potential leaching loss of soil mobile fertilizers such as N (Bar-Tal et al. 2015, Mikkelsen et al. 2015).

2.4.4 Nutrient use efficiency in potato production

Potato nutrient use efficiency (NUE) can be defined as the amount of tuber yield per unit amount of a specific nutrient applied (Zebarth et al. 2004b, Ladha et al. 2005, Baligar and Fageria 2015, Svubure et al. 2015, Steyn et al. 2016). It is therefore the ability of a potato crop to absorb nutrients from the soil or through the leaves and utilize these to produce tuber yield (Baligar et al. 2001, Ladha et al. 2005). Baligar and Fageria (2015) stated that plant NUE is based on absorption, incorporation and utilization efficiency of applied nutrients.

2.4.4.1 Nutrient use efficiency calculations in potato production

Nutrient use efficiency can be calculated and represented in different ways, but depends on the type of cropping system and data availability (Ladha et al. 2005, Dobermann 2007, Fixen et al. 2015). The most common NUE expressions are based on incremental efficiency and are defined in the following section (Baligar et al. 2001, Ladha et al. 2005, Dobermann 2007, Baligar and Fageria 2015, Fixen et al. 2015, Wani et al. 2015):

Agronomic efficiency (AE) (kg kg^{-1}): is the increase in tuber yield per unit of a specific nutrient applied. This indicator quantifies the improvement gained in crop productivity with fertilizer inputs (Fixen et al. 2015). It is calculated from Equation 2.1:

$$AE = \frac{Y_{fert} - Y_0}{NA} \quad \text{...} (2.1)$$

where Y_{fert} (kg ha^{-1}) is the tuber yield with fertilizer application, Y_0 (kg ha^{-1}) is the tuber yield without fertilizer application and NA (kg ha^{-1}) is the amount of nutrient applied.

Physiological efficiency (PE) (kg kg^{-1}): this is the increase in tuber yield per unit of crop nutrient uptake. It represents the ability of a crop to utilize nutrients absorbed from applied fertilizers to produce economic tuber yield (Fixen et al. 2015). PE is calculated using Equation 2.2:

$$PE = \frac{Y_{fert} - Y_0}{N_{fert} - N_0} \text{...} (2.2)$$

where, N_{fert} (kg ha^{-1}) is nutrient uptake by the fertilized crop, and N_0 (kg ha^{-1}) is nutrient uptake by an unfertilized crop from a control plot, and Y_{fert} and Y_0 were described earlier.

Apparent recovery efficiency (ARE) (%): is the increase in the plant nutrient uptake per unit of nutrient applied. This parameter indicates the proportion of applied nutrients taken up by the plant, as well as nutrient fraction liable to losses from the soil system (Fixen et al. 2015). It is calculated using Equation 2.3:

$$ARE = \frac{N_{fert} - N_0}{NA} \times 100 \text{ ....} (2.3)$$

The expressions of AE, PE and ARE can be used to calculate NUE of cropping systems where both fertilized and unfertilized plots exist (Ladha et al. 2005, Dobermann 2007, Fixen et al. 2015). However, in commercial potato cropping systems the entire field usually receives fertilizers, which makes such expressions difficult to apply (Fixen et al. 2015). Thus, the following expressions that are not based on incremental efficiency can be employed to calculate NUE in commercial potato fields when unfertilized or control plots are not available (Baligar et al. 2001, Dobermann 2007, Fixen et al. 2015, Wani et al. 2015).

Partial factor productivity (PFP) (kg kg^{-1}): is the ratio of tuber yield (Y) to the amount of a specific nutrient applied (NA). PFP indicates the production potential of the cropping system in response to nutrient application (Fixen et al. 2015). It can be calculated using Equation 2.4:

$$PFP = \frac{Y}{NA} \quad (2.4)$$

where Y is tuber yield in kg ha^{-1} and NA is the amount of nutrient applied as described earlier.

Nutrient use efficiency (NUE) (kg kg^{-1}): this is the ratio of tuber yield (Y) to the total amount of a specific nutrient supplied (NS). Nutrient supply is the sum of a nutrient applied in fertilizer and the initial soil nutrient content before fertilizer application (Zebarth et al. 2004a). NUE can be calculated using Equation 2.5:

$$NUE = \frac{Y}{NS} \quad (2.5)$$

where NS is nutrient supply in kg ha^{-1}.

Nutrient utilization efficiency (NUtE) (kg kg^{-1}): is defined as the amount of tuber yield (Y) per unit amount of plant nutrient uptake (N_u). NUtE can be calculated using Equation 2.6:

$$NUtE = \frac{Y}{N_u} \quad (2.6)$$

where N_u (kg ha^{-1}) is the nutrient uptake by tubers and aboveground parts.

Nutrient harvest index (NHI) (%): This is the ratio of a nutrient amount taken up in the harvested tubers to the total amount of the nutrient taken up by tubers and aboveground parts (N_u) (Zebarth et al. 2004a). NHI can be calculated using Equation 2.7:

$$NHI = \frac{N_t}{N_u} \times 100 \quad (2.7)$$

where, N_t (kg ha^{-1}) is the amount of nutrients taken up by tubers.

Partial nutrient balance (PNB) (kg ha^{-1}): is defined as the difference between nutrient output and input (Liu et al. 2003, Salam et al. 2014). This parameter indicates the amount of a nutrient taken out of the system in relation to the amount of nutrient input. It is important to note that nutrient balance calculation is a partial balance, since nutrient outputs such as runoff, volatilization and leaching, as well as nutrient inputs from biological fixation and atmospheric deposition are always excluded from the calculation (Fixen et al. 2015). PNB can be calculated using Equation 2.8:

$$PNB = [(\text{nutrient output}) - (\text{nutrient input})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.8)$$

Nutrient recovery efficiency (NRE) (kg kg^{-1}): is the ratio of total plant nutrient uptake in tubers and aboveground parts to the total nutrient supply. It indicates the extent to which the plant can absorb nutrients supplied by the soil. Nutrient recovery efficiency can be used as an indicator for nutrient loss from potato fields. However, it is difficult to quantify the proportion of nutrients supplied by the soil over time, which creates a massive uncertainty about NRE results. NRE can be calculated using Equation 2.9:

$$NRE = \frac{N_u}{NS} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.9)$$

2.4.5 Factors influencing nutrient use efficiency in potato production

Nutrient use efficiency in crop production is controlled by factors majorly related to plant nutrient demand, nutrient supply and losses from the soil-plant system (Yadav et al. 2017).

2.4.5.1 Plant nutrient demand factors

The plant genotype and its interaction with environmental factors such as temperature, solar radiation, rainfall and relative humidity, affect potato growth and development (Fageria 1998, Baligar et al. 2001, Franke et al. 2013, Baligar and Fageria 2015, Haverkort and Struik 2015, George et al. 2018). Consequently, these factors determine potato nutrient demand, as well as its nutrient recovery efficiency in a specific climatic region (Fageria 1998, Baligar and Fageria 2015). For instance, temperature affects all potato development stages, where critical temperatures lower than 20 °C and higher than 30 °C lead to a reduction in plant growth rate, which results into low nutrient recovery (Fageria 1998, George et al. 2018). Solar radiation determines light intensity and duration, which regulate photosynthesis rate and tuber yield production (Haverkort and Struik 2015). Therefore, optimum environmental conditions promote increased plant growth and nutrient recovery (Fageria 1998, Haverkort and Struik 2015).

Improved potato cultivars with high yielding potential usually have a relatively high nutrient demand and nutrient recovery rate (Baligar et al. 2001, Fageria et al. 2008, Baligar and Fageria 2015). This is because improved cultivars have enhanced nutrient absorption, translocation and dry matter production, which result in high tuber yield and NUE (Fageria et al. 2008, Baligar and Fageria 2015).

2.4.5.2 Nutrient supply factors

Soil and fertilizer aspects affect nutrient supply, which in turn impacts nutrient recovery and use efficiency.

2.4.5.2.1 Soil nutrient supply factors

The inherent soil physical and chemical constraints may influence nutrient release from soil organic matter and soil applied fertilizers (Baligar et al. 2001, Fageria and Baligar 2005, Baligar and Fageria 2015). Soil physical constraints such as soil compaction, impervious calcareous layer pans, poor soil structure and texture, poor drainage and poor water holding capacity, negatively affect plant growth and nutrient recovery (Baligar et al. 2001, Baligar and Fageria 2015). Adverse soil chemical properties such as high levels of acidity, low soil organic matter, salinity, low cation exchange capacity (CEC), elemental toxicity and low soil fertility are associated with soil plant nutrient deficiencies, which principally lead to reduced tuber yield and lower NUE (Baligar et al. 2001, Baligar and Fageria 2015).

2.4.5.2.2 Fertilizer nutrient supply factors

Fertilizer recovery and use efficiency of cropping systems is affected by factors such as type of fertilizer formulation, method, rate and time of application (Baligar et al. 2001, Baligar and Fageria 2015, Mikkelsen et al. 2015). For instance, slow and controlled release fertilizer formulations have a lower rate of mineralization and nutrient release, which ensure constant plant nutrient availability throughout the growing period (Shaviv and Mikkelsen 1993, Baligar et al. 2001, Davenport et al. 2005, Baligar and Fageria 2015). Therefore, the use of slow and controlled release fertilizer in potato production may result in increased fertilizer recovery (Baligar et al. 2001, Davenport et al. 2005, Baligar and Fageria 2015).

Fertilizer application rates lower or higher than the plant requirements may result into low NUE (Fageria and Baligar 2005, Alva et al. 2011, Baligar and Fageria 2015). Low application rates may result in reduced potato growth and low tuber yield (Alva et al. 2011, Haverkort and Struik 2015), while fertilizer application rates higher than potato nutrient requirements may result in reduced nutrient recovery (Shaviv and Mikkelsen 1993, Alva et al. 2011, Yadav et al. 2017). The time of application influences fertilizer use efficiency through synchronizing nutrient supply with crop requirements (Shaviv and Mikkelsen 1993, Zebarth and Milburn 2003, Mikkelsen et al. 2015). Timely application of fertilizers during critical potato growth stages such as tuber initiation and tuber bulking leads to increased tuber yield and NUE (Zebarth and Milburn 2003, Baligar and Fageria 2015, Haverkort and Struik 2015).

2.4.5.3 Effect of nutrient losses on nutrient use efficiency

Nutrient losses from the soil-plant system directly affect potato NUE (Shaviv and Mikkelsen 1993, Yadav et al. 2017). Soil applied nutrients can be lost through leaching, runoff, fixation, and gaseous N fertilizer losses, resulting in a low nutrient recovery (Shaviv and Mikkelsen 1993, Roberts 2008, Jiang et al. 2012, Amon-armah et al. 2013, Sharma and Bali 2017). Leaching and runoff are the principal nutrient loss pathways that prevent the plant from meeting its nutrient demand, resulting in low tuber yield and low nutrient recovery (Sharma 1999, Jiang et al. 2012, Prasad et al. 2015, Yadav et al. 2017).

Crop management practices, soil properties and weather conditions influence nutrient loss through leaching with drainage water (Sims et al. 1998, Sharma 1999, Jiang et al. 2012). High fertilizer application rates followed by excessive irrigation or a heavy rainfall event can exacerbate nutrient leaching in potato fields (Sharma 1999, Zotarelli et al. 2015, Rens et al. 2016). Also, soils of high water infiltration rate, low organic matter content and low nutrient retention capacity, such as sandy soils, are particularly conducive to nutrient leaching (Lehmann and Schroth 2003, Jiang et al. 2012, Prasad et al. 2015, Rens et al. 2016). Madramootoo et al. (1992) reported nutrient leaching from potato fields of 1.7 – 40 mg L^{-1} N, 0.002 – 0.052 mg L^{-1} P, and K leaching loss greater than 10 mg L^{-1}. Similarly, Sharma (1999) reported leached N loss from potato fields ranging from 14 – 30 kg ha^{-1}. A study by Prasad et al. (2015) revealed that 25 – 38% N of the total seasonal N input can be lost from irrigated potato fields with sandy soils. These results show that a significant amount of fertilizers can be lost from potato fields through leaching, and failure to optimize the best fertilizer management practices in potato produced on sandy soils may result in low NUE (Jiang et al. 2012).

2.5 Influence of potato-based rotation system on nutrient use efficiency

Crop rotation has been identified as a potential strategy that can increase NUE of cropping systems (Baligar et al. 2001, Davenport et al. 2005, Munoz et al. 2005, Zebarth and Rosen 2007, Jiang et al. 2012). An appropriate rotation system can allow efficient use of soil resources, specifically water and nutrients, which should increase nutrient recovery, plant growth and tuber yield (Fageria and Baligar 2005, Munoz et al. 2005). Crop rotation with catch crops can reduce nutrient leaching (Vos and Van der Putten 2000, Vos and Van der Putten 2004, Davenport et al. 2005, Munoz et al. 2005, Jiang et al. 2012), and can be beneficial in interrupting plant diseases and insect cycles, control of weeds and promote plant health (Porter and Sisson 1991, Webb et al. 2000, Larkin et al. 2012, Swain et al. 2014).

Several studies have reported that potato crops tend to leave a large proportion of residual nutrients in the soil (Vos and Van der Putten 2000, Webb et al. 2000, Vos and Van der Putten 2004, Munoz et al. 2005). For instance, a rotation sequence of potato – spring wheat – sugar beet (*Beta vulgaris* L.) – oats (*Avena sativa* L.) showed that potato applied with 407 kg ha^{-1} N left behind residual N of 112 kg ha^{-1} for the subsequent spring wheat in rotation (Vos and Van der Putten 2000). The subsequent crop in rotation after potato can therefore potentially absorb the nutrients not taken up by potato (Webb et al. 2000, Jiang et al. 2012). Potato rotations with relatively deep-rooted crops such as maize, sorghum (*Sorghum bicolor* L.), spring wheat, barley (*Hordeum vulgare* L.), oats, red clover (*Trifolium pratense* L.) and sugar beet have been widely studied (Porter and Sisson 1991, Vos and Van der Putten 2000, Webb et al. 2000, Davenport et al. 2005, Swain et al. 2014). The availability of nutrients carried-over after potato allows for a reduction of N, P and K fertilizer inputs to the subsequent crop in rotation, as can be observed in Table 2-4. Reduction of fertilizer inputs to the subsequent crop in rotation can therefore promote potato cropping system sustainability (Davenport et al. 2005, Munoz et al. 2005, Swain et al. 2014)

Table 2-4: Nitrogen (N), phosphorus (P) and potassium (K) balance (kg ha^{-1}) in a potato-based rotation sequence of potato, spring wheat, sugar beet and oats (Vos and Van der Putten 2000).

Rotation crop sequence	Inputs[a]			Exports[b]			Balance		
	N	P	K	N	P	K	N	P	K
Potato	231	45	136	185	24	223	46	21	-87
Spring wheat	82	26	77	124	22	98	-42	4	-21
Sugar beet	128	46	217	124	20	132	4	26	85
Oats	21	4	40	97	24	148	-76	-20	-108

[a]Average nutrient inputs excluding atmospheric deposition
[b]Average nutrient exports of tubers, beet roots, grains and straws

2.6 Conclusion

Potato is an important food crop with the potential to address hunger problems in many parts of the world. Water and nutrient supply are critical for increased potato growth and yield. Water and nutrient management in potato production is also important for increasing WUE, nutrient recovery and minimizing nutrient losses to the environment, thereby improving NUE. Fertilizer application using pre-plant broadcasting, band placement in rows at planting, top and side dressing after planting, foliar application during the vegetative stage and fertigation, can increase potato NUE.

Correspondingly, potato NUE increase can be achieved by optimizing factors related to plant nutrient demand, supply and nutrient losses from the soil-plant system. Appropriate rotation systems in potato production allows for more efficient use of soil resources, specifically water and nutrients, which increase nutrient recovery, plant growth and tuber yield. Increased WUE and NUE can lead to an overall improvement in productivity and ecological sustainability of potato cropping systems.

CHAPTER 3

TUBER YIELD AND WATER USE EFFICIENCY OF IRRIGATED POTATO PRODUCED ON SANDY SOILS

3.1 Introduction

Potato (*Solanum tuberosum* L.) is a high-yielding crop and requires large amounts of water and nutrients for adequate growth (Dean 1994, Munoz et al. 2005, Alva et al. 2011, Steyn et al. 2016). In addition, potato has a shallow root system with limited capacity to extend to deeper soil layers for water and nutrient uptake. This makes the crop highly sensitive to water stress, mostly during growth stages from tuber initiation until senescence (Steyn et al. 1998, Shock et al. 2007, Badr et al. 2012, Sun et al. 2015). Commercial potato production in South Africa (SA) is usually carried out under irrigation to ensure adequate water supply throughout the growing season (Steyn et al. 2016).

Sandy soils that are generally preferred for potato production have low water holding capacity and therefore require frequent water application to maintain adequate soil moisture (Steyn et al. 2016, Eissa 2019). Frequent water applications, especially on sandy soils, can lead to water loss through drainage along with leaching of nutrients such as nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Substantial water loss that primarily occurs through drainage reduces water use efficiency (WUE) and sustainability of potato production. Water use efficiency is defined as the amount of fresh tuber yield obtained per unit water received or applied through rainfall and irrigation (Shahnazari et al. 2007, Darwish et al. 2006). According to Van Ittersum and Rabbinge (1997) and Van Ittersum et al. (2013), WUE is an important indicator of sustainable potato production.

A survey by Steyn et al. (2016) to assess the efficiency of resource utilization in all potato production regions of SA indicated large differences in WUE among growers between and within production regions. The differences in WUE between regions can be explained by the differences in crop management, soil and climatic conditions that exist across regions (Steyn et al. 2016). The survey, however, did not outline the exact reasons for the large WUE differences among growers within regions, where production is done under relatively similar soil and climatic conditions. The aim of this study was to quantify overall water use and WUE of irrigated potato fields within a production region. This was achieved through detailed measurements of water inputs (rain and irrigation) and losses (evapotranspiration and drainage).

3.2 Materials and methods

3.2.1 Study site description

The study was carried out on potato fields near the village of Louwna in North West Province, SA (Figure 3-1). The North West Province is one of the regions identified to have low resource use efficiencies, specifically WUEs and nutrient use efficiency (NUE) in potato (Steyn et al. 2016). Louwna is located at 26°90´28´´ South, 24° 14´12´´ East and an elevation of 1363 m above sea level. The region is characterized by a semi-arid climate, with an average minimum temperature of 17°C and an average maximum temperature of 31°C in summer (October to April), and an average minimum temperature of 4°C and an average maximum temperature of 20°C in winter (May to September) (READ 2015). The region receives an average annual precipitation of approximately 539 mm almost exclusively between October and April (READ 2015). Potatoes in this region are planted once a year during spring (August to October). Centre-pivot irrigation systems are used to supplement the low and irregular rainfall experienced during the growing season.

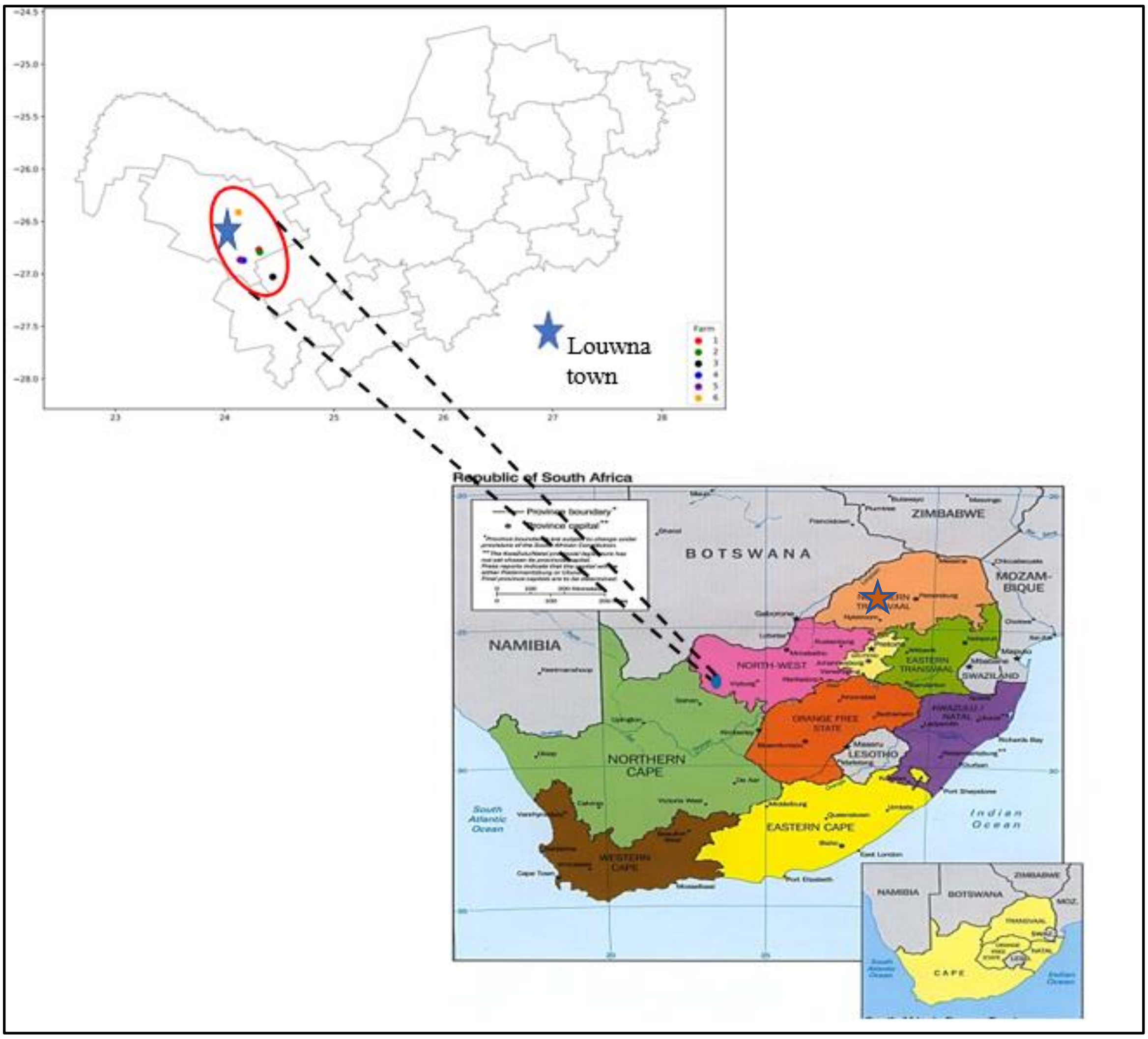


Figure 3-1: Location of each field near Louwna village, North West Province, South Africa.

3.2.2 Farm selection and crop management

Six commercial irrigated potato farms that are evenly distributed throughout the region were selected for monitoring. One field (one centre-pivot) was selected on each farm, except for Farm 1, where two fields were selected. Four fields were subjected to intensive monitoring and a further two fields were monitored less intensively. This was mainly due to limited funds, labour and measurement equipment such as drainage lysimeters (DL) and automatic weather stations (AWS).

Fields 1 – 5 were monitored during the August 2017 to February 2018 production season, while Field 6 was monitored during the August 2018 to February 2019 production season (Table 3-1). The study made use of skilled commercial growers that have access to first class technology for crop production and management. The growers have access to good quality water, and full irrigation was practiced on all fields. Five of the six selected fields planted the same potato variety, Mondial, while one field planted both Lanorma and Sifra potato varieties (Table 3-1). The potato fields monitored had sandy soils, where nutrient leaching problems could be expected (Table 3-2). Growers followed their own crop management practices related to soil preparation, planting, tillage, irrigation scheduling, fertilizer application, as well as pest, weed and disease control. Therefore, planting dates and crop agronomic practices differed among growers. The concept was to monitor WUE and NUE dynamics at field level without interfering with the farm activities. This was done through farmer surveys and field measurements regarding type, rate and method of fertilizer application, amount of rainfall and irrigation water applied, drainage and leaching measured, soil sampling and tuber yield determination.

Table 3-1: Field information regarding locality, cultivar type, and equipment installation, planting and harvesting dates.

Field	Field area (ha)	Location	Cultivar	Equipment installation date	Planting date	Harvest date	Days from planting to harvest
Intensively monitored fields							
1	19.8	26.76866°S, 24.31294 °E	Mondial	02/10/2017	26-28/09/2017	05/02/2018	132
3	10.0	27.02790°S, 24.44025 °E	Lanorma and Sifra	03/10/2017	26-29/09/2017	29/01/2018	125
4	12.7	26.87017°S, 24.17097 °E	Mondial	03/10/2017	21-29/09/2017	29/01/2018	130
6	10.0	26.41218'°S, 24.12635'°E	Mondial	19/09/2018	22-24/08/2018	14/12/2018	114
Less intensively monitored fields							
2	18.9	26.79171°S, 24.32143 °E	Mondial	02/10/2017	5-7 /09/2017	17/01/2018	134
5	10.5	26.86577°S, 24.14178 °E	Mondial	02/10/2017	10-12/10/2017	19/02/2018	132

3.2.3 Data collection and equipment installation

Each field was divided into four equal quarters of the centre-pivot, and each segment numbered from 1 to 4, as shown in Figure 3-2. The following equipment was installed on the pivots of intensively monitored fields: pressure transducer and data-logger to measure and record irrigation time, manual rain gauge and Decagon G3 drainage lysimeter (DL) to measure drainage and leaching. In the less intensively monitored fields, only the pressure transducer and data-logger were installed on the centre-pivots. The pressure transducers record pivot irrigation pressure and time. The generated data of irrigation pressure and time of each irrigation event was stored by a data-logger connected to the pressure transducer (Figure 3-3).

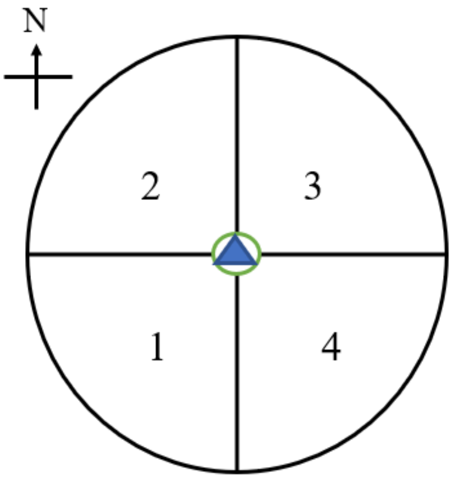


Figure 3-2: Centre-pivot quarter segments used in data collection.

3.2.4 Weather data

Complete daily weather data including minimum and maximum temperature, relative humidity, solar radiation, wind speed and rainfall were recorded by AWS installed at or close to the intensively monitored fields (Fields 1 and 3). Weather stations were installed at the same time as the DLs and other measurement equipment.

3.2.5 Soil sampling

At potato planting and after harvest soil samples were collected from each field. A total of 10 sub-samples from each quarter segment were taken at depths of 0 – 0.3 m, 0.3 – 0.6 m, and 0.6 – 0.9 m. The sub-samples per depth were combined to form a composite sample representative of the field. The composite samples were sent to the Agricultural Research Council (ARC) Small Grains Institute Soil Analyses Laboratory for standard analysis that consisted of soil particle size determination, soil density, pH (H_2O), electrical conductivity (EC) and soil nutrient status. Soil particle size distribution was determined using the Bouyoucos method (Beretta et al. 2014) (Table 3-2). Selected measured soil properties before potato planting are presented in Table 3-2

Table 3-2: Dry bulk density, pH, cation exchange capacity (CEC), organic carbon content, and sand, silt and clay percentage of the different soil layers measured for each field before potato planting.

Field	Depth (m)	Dry bulk density (g cm^{-3})	pH (H_2O)	CEC ($cmol_c$ kg^{-1})	Organic carbon (%)	Sand (%)	Silt (%)	Clay (%)
1	0-0.3	1.07	5.8	2.44	0.02	93	1	6
	0.3-0.6	1.04	5.6	2.25	0.39	92	2	6
	0.6-0.9	0.98	5.7	1.71	0.04	91	1	8
2	0-0.3	1.20	5.6	2.32	0.28	92	2	6
	0.3-0.6	1.20	5.2	1.81	0.06	92	2	6
	0.6-0.9	1.00	5.5	1.86	0.04	91	1	8
3	0-0.3	1.33	6.2	3.32	0.02	94	2	4
	0.3-0.6	1.24	6.2	2.67	0.02	94	1	5
	0.6-0.9	1.16	6.1	3.17	0.04	93	1	6
4	0-0.3	1.01	6.1	5.93	0.14	89	1	10
	0.3-0.6	1.11	6.3	7.46	0.14	85	1	14
	0.6-0.9	1.13	7.1	8.03	0.12	83	1	16
5	0-0.3	1.13	6.5	4.79	0.04	90	2	8
	0.3-0.6	1.13	6.6	6.81	0.06	87	2	11
	0.6-0.9	1.05	6.8	7.67	0.17	84	2	14
6	0-0.3	1.27	5.6	2.54	0.02	93	1	6
	0.3-0.6	1.19	5.3	2.49	0.14	93	1	6
	0.6-0.9	1.24	5.3	8.15	0.42	90	1	9

3.2.6 Yield analysis

Actual fresh tuber yields were obtained after crop harvest for each field. The potential fresh tuber yield of each field was simulated using the LINTUL–POTATO crop growth model as described by Kooman and Harverkort (1994), Haverkort et al. (2015) and Steyn et al. (2016). The LINTUL model has previously been calibrated and successfully used for potato simulation studies in southern Africa (Franke et al. 2011, Franke et al. 2013, Svubure et al. 2015, Steyn et al. 2016). The model estimates potential yield as the maximum yield attainable in production conditions without water, nutrient and biological factor limitations (Haverkort et al. 2015). The simulated potential yield is therefore based on planting and harvest dates, average seasonal temperatures and intercepted solar radiation (Steyn et al. 2016). The yield gap was expressed as a ratio of actual tuber dry matter (DM) yield to potential tuber DM yield (Svubure et al. 2015).

3.2.7 Actual and potential irrigation need measurement

The flow rate for each pivot was measured once using a transit time ultrasonic flow meter (Figure 3-3). The ultrasonic flow meter consists of two transducers that transmit and receive ultrasonic sound signals upstream and downstream within the pivot pipe carrying the water (Rajita and Mandal 2016). The transducers are clamped outside the pivot pipe apart, with the distance between them being determined by the pivot pipe diameter. A flow meter sensor records the travel time of the sound signals moving in the same direction as the water, as well as the time of those signals moving against the water flow. Sound signals move faster when traveling in the same direction as the water and slower when travelling against the water flow. The travel time difference between upstream and downstream sound signals is used to process the pivot water flow rate (Rajita and Mandal 2016). The flow rate and the irrigation time recorded by the pressure transducer were used to calculate actual irrigation amounts for the entire field.

Figure 3-3: Ultrasonic flow meter (left) and pressure transducer with CR300 data logger (right) installed on a centre-pivot system.

The potential irrigation requirement was also determined using the LINTUL–POTATO model (Haverkort et al. 2015, Steyn et al. 2016). The model calculates irrigation need as the difference between estimated total ET and precipitation recorded between planting and harvest, divided by an average irrigation efficiency of 85%, which was estimated for most of the centre-pivots in North West region (Steyn et al. 2016). Potential irrigation requirement simulations using the LINTUL-POTATO model were based on water non-limiting conditions, since all evaluated fields practiced full irrigation throughout the growing season. The daily ET was calculated by the model as the product of reference surface evapotranspiration (ET_o) and crop canopy cover (Allen et al. 1998). Model meteorological input variables such as maximum and minimum temperatures, daily solar radiation, ET_o and rainfall were obtained from AWS installed in the intensively monitored fields.

3.2.8 Drainage water sampling and analysis

Deep drainage was measured in the intensively monitored fields using the DL (Figure 3-4). This type of lysimeter intercepts drainage water using the divergence control tube (DCT). The DCT provides water suction force that prevents water outflow around the lysimeter boundary (Decagon Devices 2018). In addition, the DL consists of a 0.5 m long fibreglass wick that maintains a constant water suction, which prevents flow divergence of the water in the soil above the lysimeter. Total water suction pressure created by both the DCT and the wick increases the overall drainage water capture efficiency of the lysimeter (Zhu et al. 2002, Gee et al. 2009, Decagon Devices 2018).

The DLs were installed at about 1 m depth beyond the potato crop effective rooting zone of about 0.4 – 0.6 m. This allowed soil solution collection containing leached nutrients that would not be recovered by the potato crop. Two locations 5 m apart were selected for the lysimeter installation and intact soil core collection. The DCT was hammered at one of the locations to collect an intact soil core. Following to that, a pit of 1 m was excavated at the second location for the final DL installation. A hole of about 0.25 m diameter and 1.5 m deep was made close to the DL pit to facilitate the extension tube leading to a drainage water reservoir. Complete DL components were then assembled following the order described in the user manual (Figure 3-4) (Decagon Devices 2018). The DL was carefully lowered into the 1 m pit. The pit was then covered with soil and thereafter potatoes were re-planted in rows over the lysimeter. A sensor was lowered to the bottom of the lysimeter extension tube to measure collected drainage water depth, temperature and EC. The sensor measured data was recorded and stored by a data-logger at half-hourly intervals (Appendix 2 and 3).

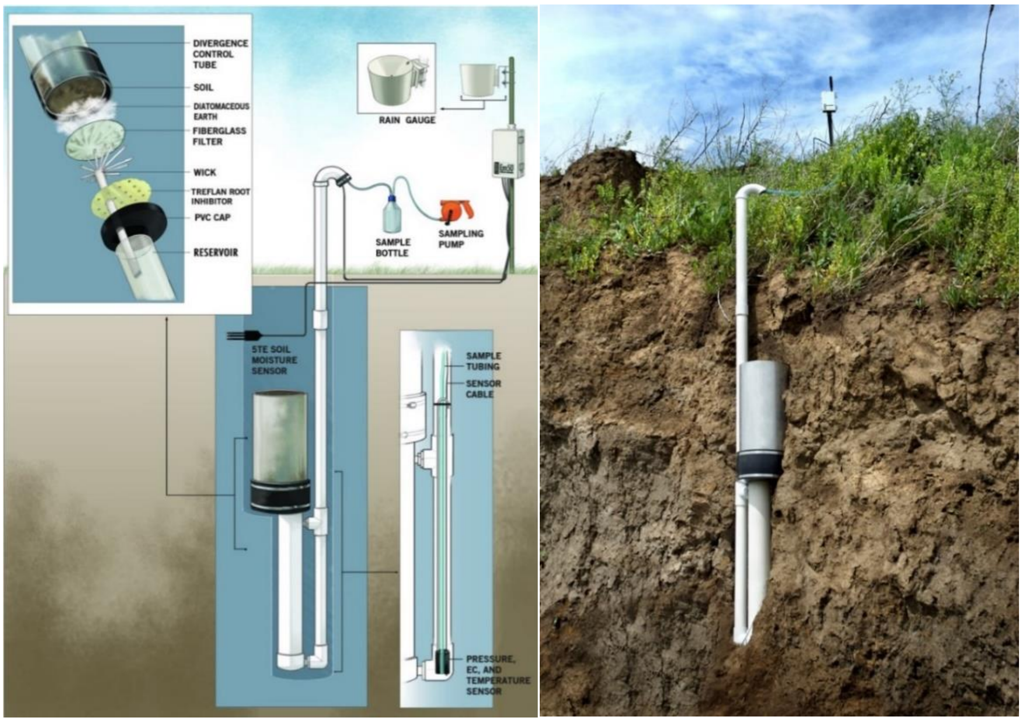


Figure 3-4: Drainage lysimeter components (from Decagon Devices 2018).

Data from the logger and drainage water samples were collected at two-weekly intervals throughout the growing season. Water extraction from the DL was carried out using 1 L glass bottles and hand-held vacuum pump. Drainage (D) was calculated using Equation 3.1.

$$D = (Vx1000) \text{ x } (10000/AL) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

where D is drainage in mm, V is total water volume pumped from the lysimeter (mL), and AL the is lysimeter collection surface area of 506.7 cm^2.

3.2.9 Water use efficiency calculation

Water use efficiency (WUE) was expressed based on rain plus irrigation, potential WUE based on simulated tuber yield and ET, and irrigation WUE based on observed irrigation amounts. Water use efficiency based on rain plus irrigation (WUE_{R+I}, kg mm^{-1}) was calculated as the ratio of the actual tuber yield (kg ha^{-1}) to the total water inputs from irrigation and rainfall (mm ha^{-1}). Potential WUE (PWUE, kg mm^{-1}) was calculated as the ratio of the potential tuber yield (kg ha^{-1}) to the simulated seasonal ET (mm ha^{-1}). Irrigation WUE (IWUE) (kg mm^{-1}) was calculated as the ratio of the actual tuber yield (kg ha^{-1}) to the irrigation amount applied (mm ha^{-1}) for each field (Darwish et al. 2006, Franke et al. 2011, Carli et al. 2014). These indices were calculated using Equations 3.2 – 3.4.

$$WUE_{R+I} = \frac{\text{Actual Tuber Yield}}{\text{Rainfall+irrigation}} \quad (3.2)$$

$$PWUE = \frac{\text{Potential Tuber Yield}}{\text{Simulated Evapotranspiration (ET)}} \quad (3.3)$$

$$IWUE = \frac{\text{Actual Tuber Yield}}{\text{Actual irrigation amount}} \quad (3.4)$$

3.2.10 Estimation of drainage

The partial soil water balance (SWB) was used to estimate drainage of the intensively monitored fields. Estimated drainage was calculated as the difference between water inputs (rain and irrigation) and water loss through ET during the potato season. This was only a partial estimation of drainage since change in soil water storage, as well as water loss through runoff, were not included in the calculation (Equation 3.5)

$$\text{Estimated drainage} = (\text{Rain} + \text{Irrigation}) - (\text{ET}) \quad (3.5)$$

3.3 Results and discussion

3.3.1 Weather during potato season

Generally, the daily maximum and minimum temperatures showed an increasing trend from planting to potato harvest during the two potato seasons: October 2017 to February 2018 and August 2018 to December 2018 (Table 3-3 and Figure 3-5). Maximum temperatures greater than 30 ^{o}C were experienced for most of the days during the two potato seasons (Figure 3-5). Daily average maximum temperature ranged from 27 – 34 ^{o}C and 24 – 35 ^{o}C for the October 2017 to February 2018 and August 2018 to December 2018 seasons, respectively. The daily average minimum temperature ranged from 9 – 16 ^{o}C and 3 – 16 ^{o}C for the October 2017 to February 2018 and August 2018 to December 2018 season, respectively (Table 3-3). Like temperature, solar radiation also showed an increasing trend, with average daily values ranging from 16 – 28 MJ m^{-2} d^{-1} during the two seasons (Table 3-3). As expected, monthly ET_o was highest during months with the highest daily average maximum temperatures (November to January). The recorded seasonal rainfall ranged between 58 – 145 mm (average of 94 mm) from the first week of October 2017 to the first week of February 2018, and 19 mm from 22 August 2018 to 14 December 2018 (Table 3-3). The climate was typical for a dry hot summer.

Table 3-3: Louwna daily average maximum and minimum temperature, daily average solar radiation, monthly average rainfall and grass reference evapotranspiration (ET_o) estimated during the potato production season from October 2017 to April 2019.

Month	Daily average maximum temperature (°C)	Daily average minimum temperature (°C)	Daily average radiation (MJ m^{-2} d^{-1})	Monthly total rainfall (mm)	Monthly total ET_o (mm)
2017					
October	27.7	9.2	17.2	38	157
November	31.3	11.3	27.8	3	212
December	32.5	14.4	26.9	19	219
2018					
January	34.0	16.0	26.3	65	222
February	30.5	16.3	22.8	72	172
March	29.8	13.5	19.8	113	138
April	27.6	11.6	13.4	152	78
May	23.8	4.6	14.2	3	94
June	22.0	0.4	13.2	2	82
July	19.4	0.3	13.6	9	80
August	23.8	2.5	16.0	0	130
September	27.8	4.3	19.8	0	165
October	29.9	10.0	23.7	5	187
November	32.4	12.3	27.1	10	222
December	34.9	15.8	27.2	12	259
2019					
January	35.6	16.6	27.3	16	252
February	32.5	16.1	22.6	67	169
March	33.5	14.4	20.6	40	171
April	26.6	11.0	15.1	196	106

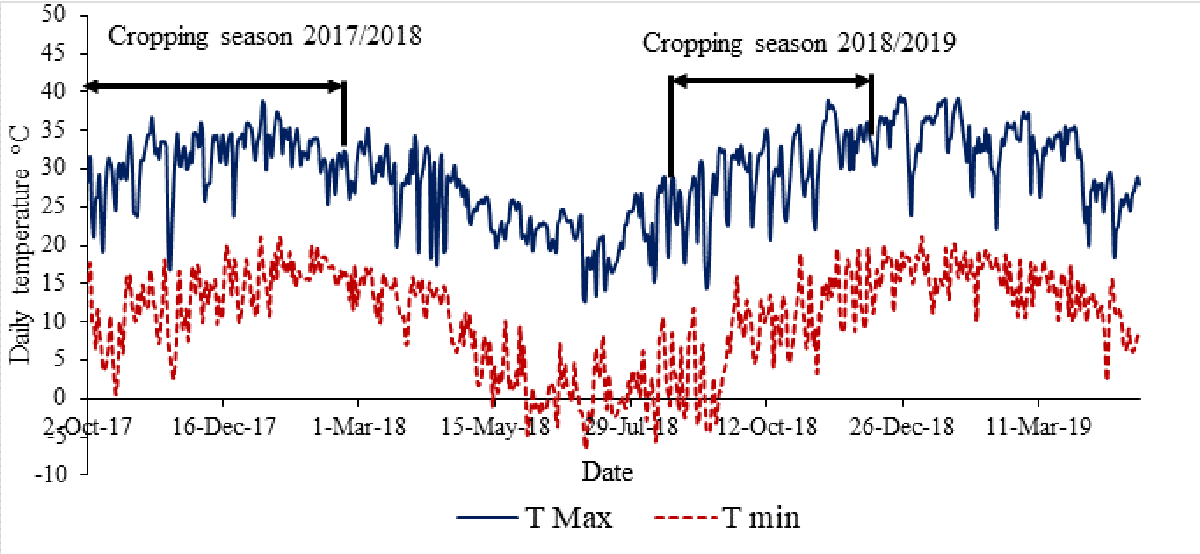


Figure 3-5: Louwna daily maximum and minimum temperatures measured from October 2017 to February 2018 and August 2018 to December 2018 potato production seasons.

3.3.2 Fresh tuber yield and total dry matter production

Actual fresh tuber yield differed widely among fields and ranged from 60 – 93 t ha^{-1}, with an average yield of 82.8 t ha^{-1} (Figure 3-6). The yields obtained by the growers were far higher than the reported national average yield of 43.7 t ha^{-1} (Potatoes South Africa 2015), and greatly exceeded the regional average yield of 58.2 t ha^{-1} reported by Steyn et al. (2016). The high tuber yields may be attributed to high production inputs, specifically water and inorganic fertilizers. Additionally, potato was grown without water limitations, which enhanced nutrient uptake and increased crop growth. The lowest actual fresh tuber yield of 60 t ha^{-1} recorded for Field 4 can be explained by yield loss due to tuber rot that was caused by waterlogging prior to harvesting. High rainfall occurred between January and February 2018, which led to waterlogging in Field 4 (Table 3-3). Field 4 had soils with relatively high clay content in the soil profile, which could have resulted in poor drainage, causing irrigation and rainfall water to accumulate in the soil upper layers (Table 3-2). In addition, the chalky calcic hard layer (Appendix 4a and b) located at approximately 1 m depth probably created a temporary water table for Field 4, resulting into poor water drainage and waterlogging.

In general, actual tuber yield matched well with the simulated potential yield (Figure 3-6). Actual tuber yields for most fields, however, were higher than the simulated potential yield, except for Field 4 where the actual yield was 25 t ha^{-1} less than the potential yield. Actual yield results suggest that the crops optimally utilized the input resources, specifically water and nutrients. The ratio of actual to potential tuber DM yield of five out of the six farms exceeded 1.0 (Table 3-4). A study carried out in 16 potato producing regions of SA reported values of actual to potential yield ratio ranging from 0.26 – 0.84, with an average value of 0.6 (Steyn et al. 2016). The authors concluded that regions with actual to potential yield ratios close to 1.0 efficiently utilized the available resources and have limited scope to further increase yields under similar production conditions (Steyn et al. 2016). A similar conclusion can be drawn for fields investigated in the present study.

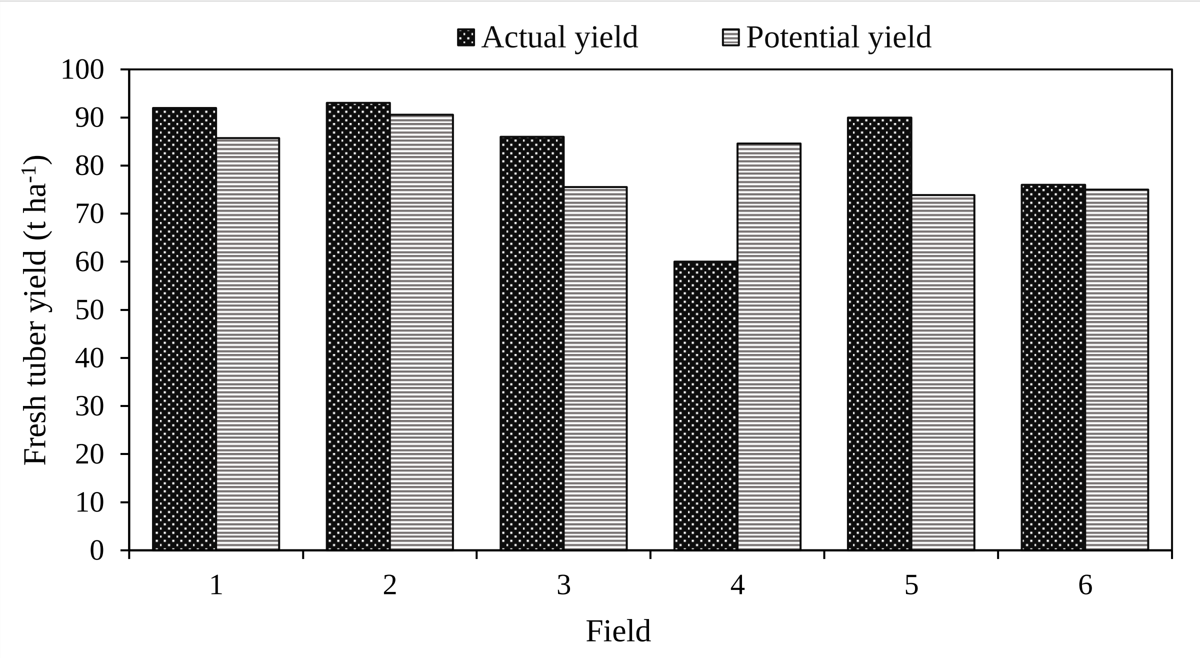


Figure 3-6: Actual and simulated potential fresh tuber yield obtained for each field.

Achieving actual yields higher than the potential yield is practically impossible since it requires perfect crop and soil management, which cannot be achieved at large scale commercial production (Van Ittersum et al. 2013, Steyn et al. 2016, Guilpart et al. 2017). In addition to soil and crop management, abiotic (extreme weather parameters) and biotic (pests and diseases) stress factors usually force actual yields to level off at 75 – 85% of the potential yield (Van Ittersum et al. 2013). Actual yields higher than simulated potential yield observed in the present study may be explained by potential yield underestimation by the LINTUL-POTATO growth model for most fields. Potato phenological development stages are highly dependent on temperature, implying that growth and DM production increase with temperature increases within the optimal range for the crop (Haverkort and Kooman 1997, Franke et al. 2011, Haverkort et al. 2015). However, at very low and very high temperatures, the model simulates reduced photosynthesis and DM production, resulting in low potential yield estimates (Franke et al. 2011, Haverkort et al. 2015). For instance, photosynthesis is reduced when average daily temperature falls below 15 ^{o}C or when the maximum temperature exceeds 30 ^{o}C, whereas temperatures lower than 3 ^{o}C and higher than 35 ^{o}C result in no photosynthesis (Franke et al. 2011, Haverkort et al. 2015). Accordingly, the model may have simulated potato heat stress when very high temperatures (greater than 30 ^{o}C) were experienced during some days of the season (Figure 3-5), while in practice that may not have affected crop growth and actual total DM production (Table 3- 4). Similarly, the model simulated low potential yield in the Sandveld potato producing region of South Africa for mid-summer plantings (December – January) during days when very high temperatures were experienced (Franke et al. 2011). Optimal growth at these high temperatures may be possible due to a cooling effect of the sprinkler irrigation used (Steyn 2019 Personal communication). Accordingly, the micro-environment around the irrigated potato canopy is usually a few degrees lower than the daily ambient temperature measured at about 2 m height by the weather station placed in a dry environment next to the field.

Table 3-4: Actual and potential tuber dry matter (DM) yield, actual aboveground DM yield, and yield gap ratio of actual to potential tuber DM yield of each field.

Field	Actual tuber DM yield ($t\ ha^{-1}$)	Potential tuber DM yield ($t\ ha^{-1}$)	Actual aboveground DM yield ($t\ ha^{-1}$)	Yield gap (Actual: potential tuber DM yield)
1	18.4	15.0	6.1	1.2
2	18.6	15.9	6.2	1.2
3	17.2	13.2	5.7	1.3
4	12.0	14.8	4.0	0.8
5	18.0	15.0	6.0	1.2
6	15.2	13.1	4.7	1.2
Average	16.6	14.5	5.5	1.1

3.3.3 Water use and use efficiency

3.3.3.1 Water inputs and evapotranspiration

Daily and cumulative water input amounts through irrigation and rainfall and cumulative ET during the October 2017 to February 2018 potato season for Field 1 – 5, and August 2018 to December 2018 season for Field 6 are presented in Figures 3-7 and 3-8. There was a large variation in the total water amount applied between the fields, with values ranging from 609 – 1141 mm (average of 982 mm). Field 6 received the least total water amount of 609 mm, while Field 4 received the highest total water amount of 1141 mm (Figure 3-8 c and a). The average daily rain plus irrigation was higher than the daily potential crop ET throughout the season for all fields. Field 1, however, can be considered as an anomaly since 103 mm daily irrigation of was applied between 23 – 24 of November 2017 when the center pivot was turned on for longer hours due to mechanical failure. This led to a sharp increase in cumulative water inputs as compared to cumulative ET for this field (Figure 3-7a). The cumulative ET ranged between 479 – 785 mm, with an average of 701 mm. Therefore, a large difference between the cumulative rain plus irrigation and cumulative ET was observed for all fields (Figures 3-7 and 3-8).

The differences in potato cultivar, crop agronomic practices, soil and climatic conditions make comparison of water inputs and potential ET results between growers and areas difficult. For instance, hot and dry environments of high vapor pressure deficit require high water inputs in response to high ET experienced in such areas. The reported seasonal water requirements for potato ranges from 300 – 700 mm, depending on the weather conditions and the length of the growing season (Panigrahi et al. 2001, Vos and MacKerron 2006, Shock et al. 2007).

Potato water inputs of the present study can be compared to input ranges applied to potato produced under similar hot and dry conditions. The irrigation water inputs for most of the fields was higher than the irrigation amount ranging from 300 – 650 mm applied to potato in North West Province of SA (Steyn et al. 2016). In the same study, potato irrigation requirements of 382 mm and 516 mm for dry regions of North West and South Western Free State, respectively were estimated (Steyn et al. 2016). Irrigation amount of 328 mm in response to 100% of crop ET was applied to potato in arid climate region of Nile Delta of Egypt (Badr et al. 2012).

The cumulative ET recorded for the entire potato crop season in Fields 1, 2, 3, 4, 5 and 6 was 785, 728, 688, 752, 774 and 479 mm, respectively (Figures 3-7 and 3-8). The total water inputs for some of the fields were far higher than the respective cumulative ET, which is clear evidence that the growers do not use water management and irrigation scheduling tools, resulting into over-irrigation.

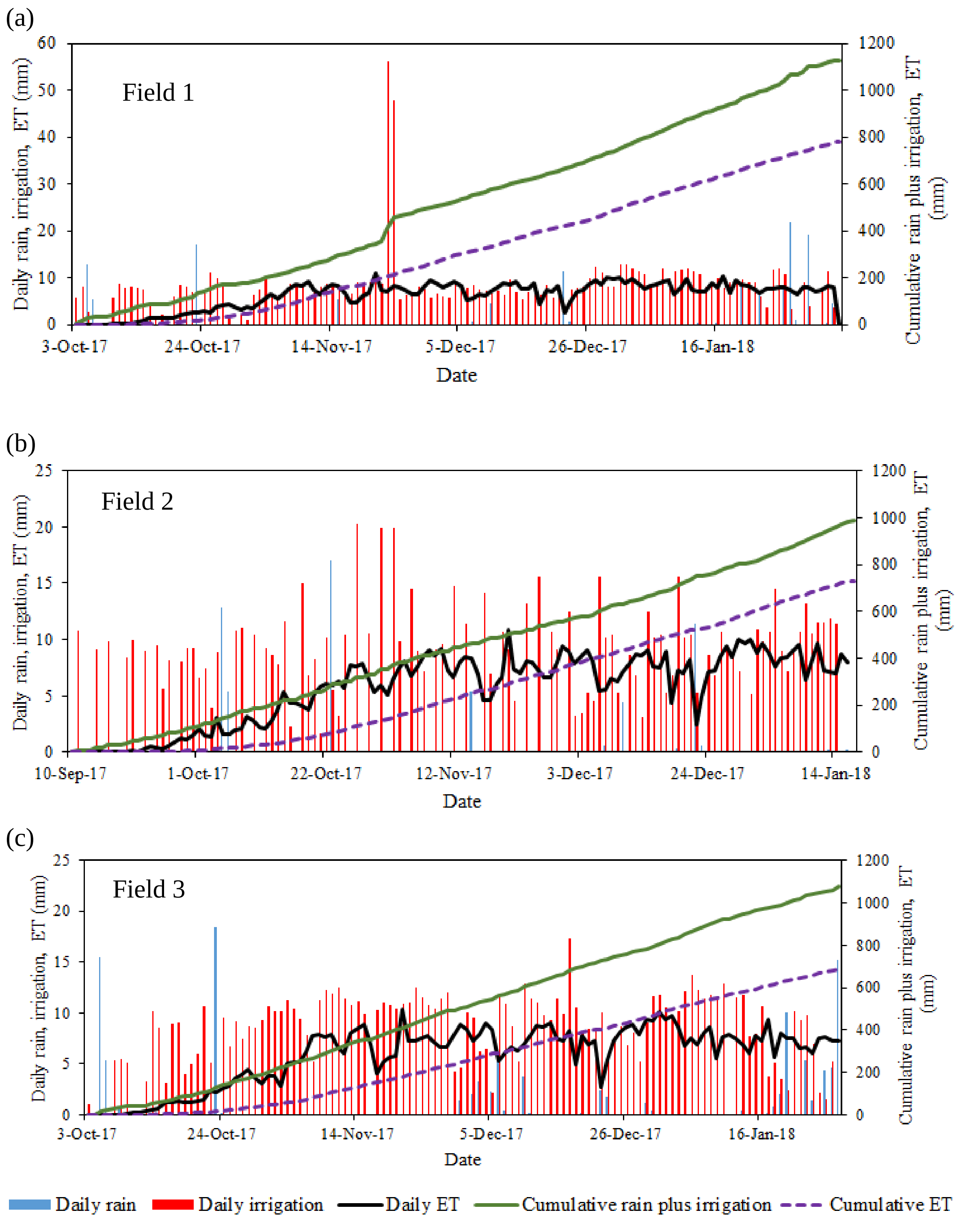


Figure 3-7: Daily rain, irrigation, and evapotranspiration (ET), cumulative rain plus irrigation and cumulative ET for Field 1 (a), Field 2 (b) and Field 3 (c) applied to potato from planting to harvest.

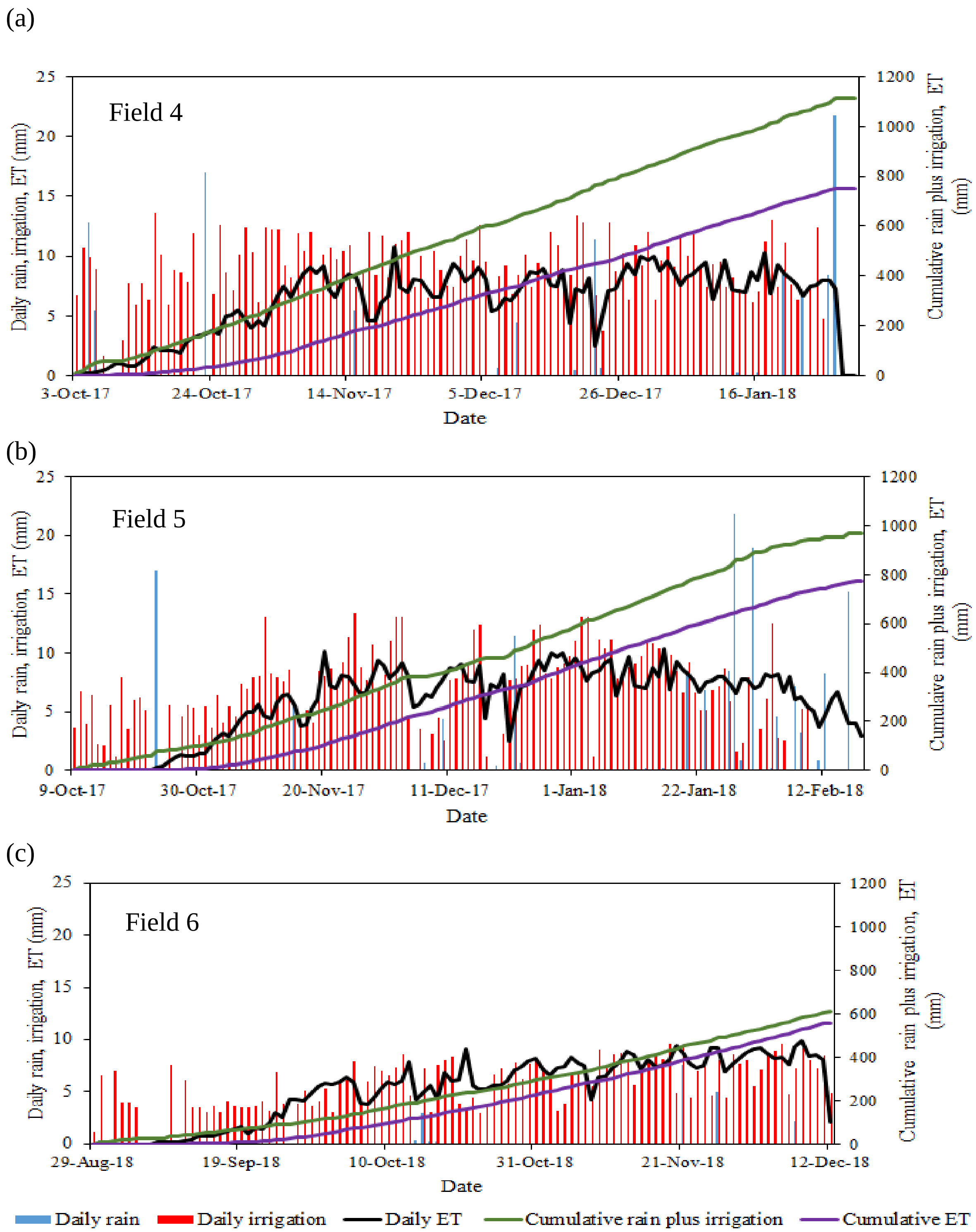


Figure 3-8: Daily rain, irrigation, and evapotranspiration (ET), cumulative rain plus irrigation and cumulative ET for Field 4 (a), Field 5 (b) and Field 6 (c) applied to potato from planting to harvest.

3.3.3.2 Water use efficiency

Table 3-5 shows observed irrigation amount, seasonal rainfall, calculated irrigation requirement based on estimated ET, rainfall and crop water requirements, as well as the calculated WUE_{R+I}, PWUE and IWUE. The observed irrigation substantially exceeded the respective simulated irrigation requirements for all fields, except for Field 6 (Table 3-5). This suggest that potato was over-irrigated, which presented high drainage and nutrient leaching risks.

Fields with observed irrigation amounts close to calculated irrigation requirement had the highest WUE_{R+I}, PWUE and IWUE (Table 3-5). The WUE_{R+I} varied greatly among fields and ranged from 53.8 – 124.8 kg mm^{-1}, with an average of 89.6 kg mm^{-1}. Lowest WUE_{R+I} was recorded for Field 4 (53.8 kg mm^{-1}), which had the highest total water inputs (1411 mm) and obtained the lowest actual tuber yield (60 t ha^{-1}). Highest WUE_{R+I} (124.8 kg mm^{-1}) was recorded for Field 6, which received the lowest total water amount (590 mm) and still obtained good yields (76 t ha^{-1}).

The WUE_{R+I} results of the present study fall in the WUE_{R+I} range of 90 – 129 kg mm^{-1} for the North West potato production region (Steyn et al. 2016). Similarly, Badr et al. (2012) reported WUE_{R+I} range of 90 – 195 kg mm^{-1} for potato produced in an arid climate region of Egypt. In contrast, lower WUEs of 17 – 45 kg mm^{-1} were recorded for irrigated potato produced under hot and dry conditions in Tashkent, Uzbekistan with mean temperatures between 15 – 29 ^{o}C and relative humidity range of 25 – 58% (Carli et al. 2014). The very low WUE was attributed to relatively high irrigation amounts ranging from 692 – 1341 mm and very low yields between 13 – 37 t ha^{-1} (Carli et al. 2014). Therefore, WUE_{R+I} of the present study was relatively high considering that potato was produced under hot and dry conditions. This high WUE_{R+I} can be attributed to the relatively high actual tuber yield obtained for each field. Similarly, Badr et al. (2012) stated that high WUE can be achieved by maintaining high yield with reduced water use, which is attainable through the implementation of irrigation scheduling to reduce water losses through drainage (Badr et al. 2012).

The scope for WUE_{R+I} improvement can be represented by the difference between WUE_{R+I} and PWUE (Van Ittersum et al. 2013). Potential WUE is the maximum WUE that can be achieved through improved management of total water applied (Van Ittersum et al. 2013, Svubure et al. 2015). Potential WUE in this study was obtained from the division of potential tuber yield by the modelled ET (Franke et al. 2011). The results of the current study showed a relatively large difference between the WUE_{R+I} and PWUE for all fields, except for Field 6 (Table 3-5). This suggests that the growers have room to improve WUE_{R+I} of potato production.

The IWUE indicator facilitated the assessment of irrigation water usage in terms of harvestable yield production. Irrigation WUE ranged from 59.3 – 128.8 kg mm^{-1}, with an average of 98.6 kg mm^{-1}. The lowest IWUE (59.3 kg mm^{-1}) was recorded for Field 4, which had the highest irrigation amount of 1011 mm and the lowest tuber yield of 60 t ha^{-1}. On the other hand, Field 6 recorded the highest IWUE of 128.8 kg mm^{-1} following the lowest irrigation amount of 590 mm and an acceptable tuber yield of 76 t ha^{-1}. These results are comparable to the IWUE range of 80 – 135 kg mm^{-1} reported for the Sandveld region of SA for potatoes planted in early summer (September – November) (Franke et al. 2011).

Table 3-5: Seasonal rainfall, observed irrigation amount, simulated irrigation requirement, estimated seasonal ET, water use efficiency based on rain and irrigation (WUE_{R+I}), potential water use efficiency (PWUE) and irrigation water use efficiency (IWUE) of potato production for all fields.

Field	Seasonal rainfall (mm)	Observed irrigation applied (mm)	Simulated irrigation requirements (mm)	Simulated seasonal ET (mm)	WUE_{R+I} (kg mm^{-1})	PWUE (kg mm^{-1})	IWUE (kg mm^{-1})
1	128	906	810	777	88.9	110.3	101.5
2	58	900	800	728	97.0	124.5	103.3
3	110	967	708	688	79.9	109.7	88.9
4	104	1011	795	752	53.8	112.5	59.3
5	145	822	786	774	93.1	95.5	109.5
6	19	590	598	555	124.8	135.1	128.8
Average	94	866	750	712	89.6	114.6	98.6

A non-linear regression relationship between irrigation amount and fresh tuber yield was observed for all fields (Figure 3-9). A similar relationship ($y = -0.0092x^2 + 7.52x – 409.47$, $R^2 = 0.980$) was reported by Yuan et al. (2003). Conversely, a linear response of tuber yield to total water applied was obtained for potato produced in arid climate region of Egypt ($y = 0.092x + 10.55$, $R^2 = 0.973$) (Badr et al. 2012). It is important to note that tuber yield response to water applied depends on the weather conditions during the season, which also makes comparison between different production areas difficult.

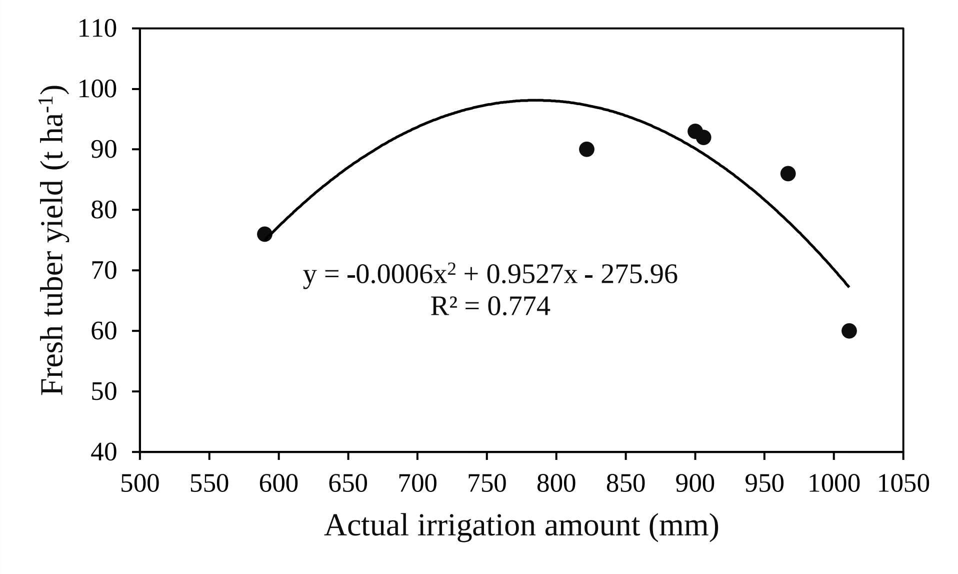


Figure 3-9: Relationship between actual fresh tuber yield and actual irrigation amount (including values obtained for all fields).

3.3.4 Drainage water losses from potato fields

During the potato growing season, drainage water was only collected from Field 1. Field 3 recorded no drainage because it possesses a calcic chalky layer between 0.7 – 1 m in the profile, which probably impeded water movement beyond 0.7 m depth (Appendix 4). Field 4 recorded no drainage probably due to limited water movement caused by slightly high clay content (10 – 16%), in addition to calcic chalky layer within the soil profile between 0.8 – 1 m. The absence of drainage for Field 6 can be explained by the relatively low irrigation applications practiced by the grower. Additionally, average daily irrigation amounts for Field 6 were generally close to daily ET for most of the days during the season, so, there was less excess water to drain beyond the 1 m depth for this field. Although drainage was not measured for Fields 3, 4 and 6, it may still have occurred via sub-surface lateral flow that is not intercepted by the DL. The DL used in this study controls soil water bypass flow using the DCT. However, diversion of low intensity drainage away from the lysimeter could have occurred, resulting in no drainage for Fields 3, 4 and 6 (Gee et al. 2009, Decagon Devices 2018). Decagon G3 DL has a low drainage collection efficiency in texture extremes such as very sandy, unstructured and fine textured soils especially at low drainage flux rates (Gee et al. 2009, Decagon Devices 2018).

Field 1, however, recorded drainage because it has low clay percentage ranging from 6 – 8% in the soil profile, with rather deep limiting chalky layer (beyond 1 m depth) and it received high water inputs of 1126 mm (Figure 3-10). Furthermore, the cumulative total water inputs greatly exceeded the cumulative ET throughout the season (Figure 3-10).

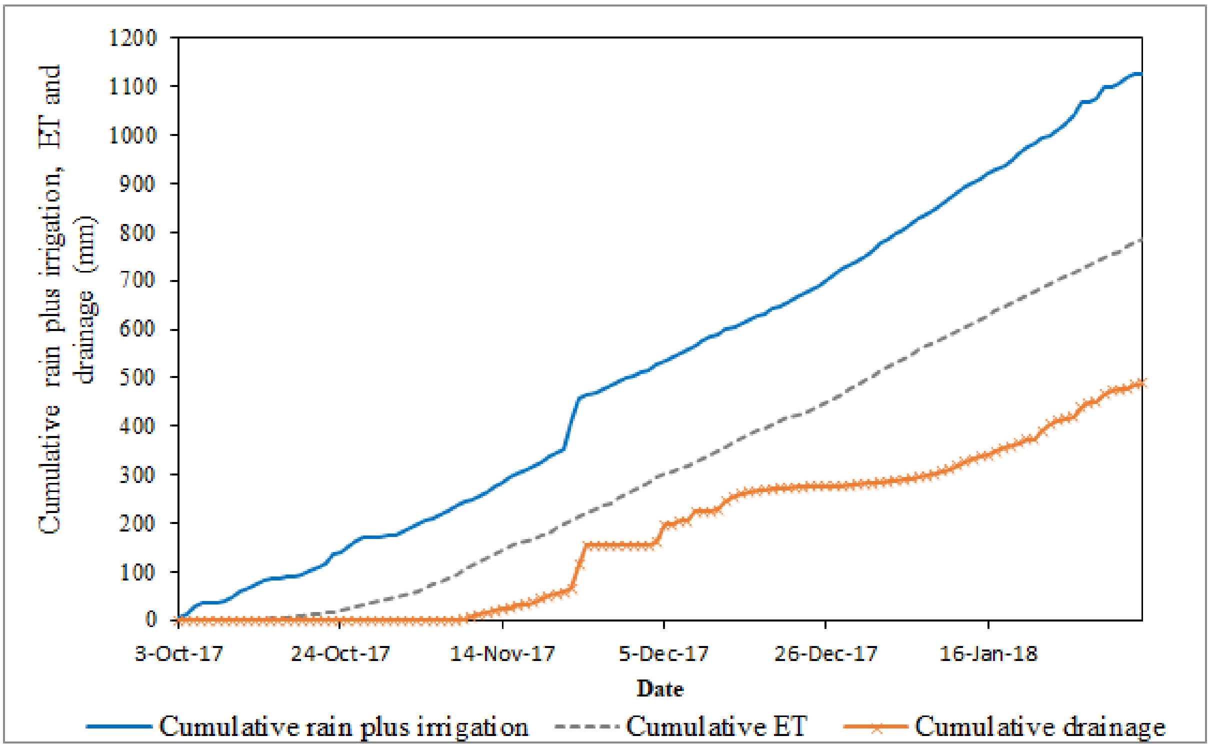


Figure 3-10: Cumulative rain plus irrigation, cumulative evapotranspiration (ET) and cumulative drainage for Field 1.

For Field 1, the cumulative drainage increased sharply by 104 mm between 23 – 25 November (Figure 3-10). This was because the irrigation boom coincidentally came to a standstill over the lysimeter location due to a power failure, and drainage of about the same amount as the irrigation was recorded over the two days. Thereafter, drainage increased gradually until the end of the potato season. A total drainage amount of 488 mm was collected by the end of the potato season, which represents 47% of the total water inputs. Comparably, Arauzo and Valladolid (2013) reported drainage amounts ranging from 156 – 228 mm, representing 25 – 35% of the total water inputs (633 mm) for irrigated potato grown on coarse textured alluvial soils in northern Spain. Drainage water amounts ranging from 8 – 250 mm were also recorded for potato of different planting dates in a three year potato-based rotation experiment carried out on sandy soil in south-west Sweden (Neumann et al. 2012).

The current and past drainage results reveal that there is a direct relationship between the intensity of water inputs and drainage (Neumann et al. 2012, Arauzo and Valladolid 2013). In addition, the rate of downward water movement in the soil profile is largely determined by soil texture, structure, initial soil water content and crop management practices (Merdun 2012, Arauzo and Valladolid 2013). Sandy soils that inherently have low organic matter content and are of poor water holding capacity, therefore, present an increased risk to drainage and nutrient loss through leaching (Prasad et al. 2015). Initial soil water content close to field capacity renders the soil prone to high drainage especially when irrigation is applied, while crop management in terms of soil tillage increases water infiltration and drainage (Merdun 2012, Arauzo and Valladolid 2013).

Current study results suggest that the variability in the measured drainage in intensively monitored fields was mainly caused by differences in the soil profile physical characteristics. Moreover, differences in climatic conditions and crop management practices can also cause variations in drainage from potato fields located in the same agro-ecological zone (Arauzo and Valladolid 2013). These factors make comparison of drainage results between growers difficult. Thus, knowledge of soil physical characteristics such as texture, structure and current soil water content is important in the adoption of water management practices intended to minimize water loss through drainage.

3.3.4.1 Comparison of estimated and measured drainage

A soil water balance (SWB) equation was used to calculate drainage for the intensively monitored fields (Fields 1, 3, 4 and 6) (Table 3-6). In the SWB calculation, water losses through runoff were not included. While no drainage was observed in the DLs for Fields 3, 4 and 6, SWB estimated relatively high drainage for these fields. Only for Field 1, the measured drainage was higher than the calculated drainage (Table 3-6). This was partly due to the over-irrigation application (104 mm) between 23 – 24 of November 2017 which resulted into drainage of about 100 mm over the two days (Figure 3-7a).

Table 3-6: Water inputs (rainfall and irrigation), water loss through evapotranspiration (ET), estimated and measured drainage for Fields 1, 3, 4 and 6.

Field	Water inputs		Water use	Estimated drainage (mm)	Measured drainage (mm)
	Rainfall (mm)	Irrigation (mm)	ET (mm)		
1	128	998	785	341	488
3	129	966	870	225	0
4	130	1011	752	389	0
6	19	590	488	121	0

3.4 Conclusions

On-farm assessment and detailed measurement of potato WUE for fields within a production region provided useful information that can be used to explain the exact reasons for the large WUE differences among growers. Relatively high yield and WUE were obtained by the growers, although these were seen to vary between potato fields. The observed yield and WUE variations between fields are attributed to the differences in irrigation rates and rainfall received during the season. High water inputs are used by the growers which can increase the risk of water loss through drainage. Soils with a loamy sand texture and a shallow impermeable calcic hard pan layer between 0.8 – 1 m in the profile were less susceptible to vertical drainage. However, these fields face a higher risk of waterlogging during periods of high rainfall, which potentially leads to tuber rot and low WUE. Growers can increase WUE by obtaining high yields with reduced water inputs, which can be done by irrigating below the ET rate. This reduces the risk of water loss through drainage. Finally, knowledge of soil physical characteristics such as texture and structure are important in the adoption of objective irrigation scheduling practices intended to minimize water loss through drainage and increase WUE in irrigated potato.

CHAPTER 4

IN-FIELD MEASUREMENT OF NUTRIENT BALANCES AND NUTRIENT USE EFFICIENCY OF IRRIGATED POTATO GROWN ON SANDY SOILS

4.1 Introduction

Potato (*Solanum tuberosum* L.) is a potentially high-yielding crop which requires large amounts of water and nutrient resources to achieve profitable yields (Dean 1994, Munoz et al. 2005, Alva et al. 2011, Steyn et al. 2016). Even more so, because potato production is usually carried out on coarse-textured soils of low organic matter content and fertility, with poor water and nutrient holding capacity (Alva 2010, Rens et al. 2016). Such soils demand frequent irrigation and fertilizer addition for adequate soil water and fertility maintenance (Errebhi et al. 1998, Steyn et al. 2016, Zhou et al. 2018). Adequate supply of both water and nutrients essentially promotes optimum potato growth, increases tuber yield, and minimizes nutrient loss to the environment (Cambouris et al. 2008, Banerjee et al. 2016, Hailu et al. 2017).

Frequent irrigation and application of large amounts of fertilizer, however, can lead to nutrient loss, mainly through leaching, which reduces potato nutrient use efficiencies (NUE) (Alva 2010, Zotarelli et al. 2014, Prasad et al. 2015). Relatively high nutrient leaching is usually observed in potato, mainly because of the intensive tillage before planting (Torstensson et al. 2006, Prasad et al. 2015, Woli and Hoogenboom 2018). In addition, sandy soils on which potato is usually and preferably grown, are prone to drainage and nutrient leaching, especially under irrigation conditions (Steyn et al. 2016, Woli and Hoogenboom 2018). Also, the fact that potato has a sparse and shallow root system with limited ability to explore a large soil volume for water and nutrients, leads to relatively lower recovery of nutrients applied (Alva 2006, Prasad et al. 2015, Rens et al. 2016). For example, Cambouris et al. (2008) documented that potato tubers can only recover around 45% of the nitrogen (N) fertilizer applied. Similarly, average fertilizer N recovery of 33% and 56% was obtained in irrigated potato grown on coarse-textured soil during two production seasons (Errebhi et al. 1998). In the same experiment, nitrate (NO_3^-) leaching ranged from 71 – 257 kg ha^{-1} for the two growing seasons (Errebhi et al. 1998).

Nutrient recovery and leaching within a cropping system largely depends on fertilizer application rate and timing, crop type, soil type, and amount and distribution of rainfall and irrigation over the growing season (Alva 2006, Zotarelli et al. 2014, Woli and Hoogenboom

2018). (Munoz et al. 2005). Root-zone nutrient loss through leaching affects soil nutrient phytoavailability, thereby limiting plant growth, production and yield as well as resulting in lower NUE. Nutrient use efficiency has been used as an indicator for ecological sustainability of production systems (Van Ittersum and Rabbinge 1997, De Vries et al. 2010, Steyn et al. 2016). This indicator can also be used to compare productivity of potato cultivars, individual growers and production regions (Fageria et al. 2008, Franke et al. 2011, Steyn et al. 2016).

Previous studies carried out by Franke et al. (2011) and Steyn et al. (2016), showed that potato producing regions of South Africa (SA) with very sandy soils had the lowest NUE. Large NUE differences among potato growers were also observed within production regions of similar soil and climatic conditions (Franke et al. 2011, Steyn et al. 2016). However, the studies did not outline the exact reasons for the large NUE differences among potato growers producing in relatively similar soil and climatic conditions. Therefore, the present study aimed at quantifying the variability in NUE among potato growers within a single production region of SA. This was achieved through intensive measurements of water and nutrient application rates, plant nutrient uptake, water drainage and nutrient leaching. The study also aimed at estimating nutrient balances for the various fields studied after the potato harvest to recommend nutrient management practices in potato production systems.

4.2 Materials and methods

4.2.1 Soil sampling and analysis

Soil samples from each field were collected at potato planting and after harvest. For the full sampling procedure, refer to Chapter 3. Composite soil samples were sent to the Agricultural Research Council (ARC) Small Grains Institute’s Soil Analyses Laboratory located in Bethlehem, Free State Province, SA, for standard chemical analysis that consisted of soil pH, electrical conductivity (EC) and soil nutrient status. Soil mineralizable N was not analysed because of concern resulting from delayed analysis of the samples, with increased storage time potentially leading to N transformations through mineralization, immobilization, denitrification and volatilization. Phosphorous was extracted using the P- Bray 1 method (Boem et al. 2011), and the cations K, Ca, Mg and S were extracted using ammonium acetate solution (Roberts et al. 1971). The nutrients P, K, Ca, Mg and S were analysed using Inductively Coupled Plasma- Optical Emission Spectrometer (ICP-OES) (Hou and Jones 2000).

The soil mineral (kg ha^{-1}) content was calculated from the product of soil mass (kg_{soil} ha^{-1}) of each layer (0.3 m depth) and the nutrient concentration (mg kg_{soil}^{-1}) as presented in Equation 4.1

$$\text{Soil mineral content} = \text{Soil mass x nutrient concentration x } 10^{-6} \text{ kg mg}^{-1} \ldots\ldots\ldots\ldots (4.1)$$

Soil mass (kg_{soil} ha^{-1}) was calculated as the product of soil volume (m^3) and dry bulk density (kg_{soil} m^{-3}) from Equation 4.2.

$$\text{Soil mass} = 10000 \text{ m}^2 \text{ ha}^{-1} \text{ x } 0.3 \text{ m x dry bulk density} \ldots\ldots\ldots\ldots (4.2)$$

Soil density for each layer are presented in Table 3-2

4.2.2 Plant tissue sampling and nutrient analysis

Potato plant sampling involved collection of whole plant samples one week before complete plant desiccation. Representative plant samples were obtained from each quarter of the centre-pivot. Four randomly selected spots of 1 m^2 were sampled per quarter to form a composite sample for the entire field. The plants were separated into leaves, stems and tubers, and thereafter washed with running tap water, sliced (tubers) and dried in an oven with forced air circulation at 60 °C until constant dry mass. The dried samples were weighed to obtain whole plant dry matter (DM) production. Dried plant samples were sent to Nvirotek Laboratory for nutrient status analysis. Plant N concentration was analysed using the Dumas method that involves dry combustion and analysis of all N constituents in an automated LECO CHN 600 machine (Simonne et al. 1997). The elements P, K, Ca, Mg and S were analysed using ICP-OES after acid digestion of the samples using nitric acid (Hou and Jones 2000). The nutrient concentration of each plant part was multiplied by the respective DM to obtain nutrient uptake. Whole plant nutrient uptake was obtained from the sum of nutrient uptake in roots, leaves, stems and tubers.

4.2.3 Irrigation and drainage water nutrient analysis

Irrigation water samples were obtained from water reservoir dams of all monitored fields. Drainage water was analysed for nutrient status to determine nutrient leaching loss from intensively monitored fields. For drainage water collection and sampling methodology, refer to Chapter 3.

Representative irrigation and drainage water samples of about 600 ml were sent to Nvirotek Laboratory for standard chemical analysis, specifically for pH, EC and nutrient status. Inorganic N concentration was determined using the Dumas method (Simonne et al. 1997), while P, K, Ca, Mg and S were analysed using ICP-OES (Hou and Jones 2000). Nutrients applied with irrigation water were calculated as the product of nutrient concentration in the irrigation water and total seasonal irrigation amounts presented in Table 3-5 (Chapter 3).

The amount of nutrients leached (NL kg ha^{-1}) in drainage water was calculated from Equation 4.3

$$NL = [D \times Ce \times 10^{4} \text{ L ha}^{-1}] \times 10^{-6} \text{ kg mg}^{-1} \quad \ldots\ldots (4.3)$$

where D is drainage (mm) and Ce is the nutrient concentration (mg L^{-1}) in drained water.

4.2.4 Nutrient use efficiency calculation

Nutrient use efficiency was expressed using non-incremental efficiency parameters: partial nutrient balance (PNB), partial factor productivity (PFP), nutrient utilization efficiency (NUtE) and nutrient harvest index (NHI) (Baligar et al. 2001, Dobermann 2007, Fixen et al. 2015, Wani et al. 2015). Non-incremental efficiency parameters are preferred to calculate NUE of cropping systems without unfertilized or control plots (Baligar et al. 2001, Dobermann 2007, Fixen et al. 2015, Wani et al. 2015). The parameters PNB, PFP, NUtE and NHI were calculated using Equations 2.8, 2.4, 2.6 and 2.7, respectively.

4.2.5 Statistical analysis and potato production sustainability

Correlations between nutrient inputs and tuber yield were assessed using Spearman Rank with the help of SAS® Computer program, version 9.4 (SAS 2008).

4.3 Results and discussion

4.3.1 Potato nutrient input sources

4.3.1.1 Initial soil chemical properties before potato planting

The initial soil chemical properties before potato planting for each field are presented in Table 4-1. The soil pH ranged from 5.3 – 7.1 for all fields and is within the ideal pH range of 4.9 – 6.4 for potato production. Soils with pH lower than 4.9 may result in nutrient deficiencies of mainly P, K, Ca and Mg, as well as toxicities of Mn and Al, which affect nutrient use of potato (Rosen 2018). Fields 1, 2 and 6 showed slightly acidic soils as compared to the other fields that had close to neutral soil pH. Generally, the soil of all fields showed a low saturated paste electrical conductivity (EC_e), since the values were less than 1.0 mS cm^{-1}. This implied that the soils posed no salinity effects to potato that has been classified as a moderately salinity tolerant crop (Shannon and Grieve 1999). Cation exchange capacity (CEC) ranged from 1.71 – 8.15 $cmol_c$ kg^{-1} within the 0 – 0.9 m depth for all fields. Fields 4 and 5 showed the highest average soil profile CEC of 7.1 and 6.4 $cmol_c$ kg^{-1}, respectively. This can be explained by the increasing clay content from top to bottom soil layers of the profile for the two fields (Table 3-2: Chapter 3). Clay soil particles provide large negatively charged surfaces that bind exchangeable cations, including K, Ca and Mg within the soil solution (Essington 2015). As expected, Fields 1, 2, 3 and 6 with low soil clay content had low CEC values (Table 4-1).

Table 4-1: Soil pH, saturated paste electrical conductivity (EC_e), cation exchange capacity (CEC), available phosphorus (P), exchangeable potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) and sulphur (S) content (kg ha^{-1}) measured in different soil layers for each field before potato planting.

Field	Depth (m)	pH (H_2O)	EC_e (mS cm^{-1})	CEC ($cmol_c$ kg^{-1})	P[a]	K	Ca[b]	Mg	S[b]
					kg ha^{-1}				
1	0-0.3	5.8	0.78	2.44	180.5	498.7	998.3	154.1	484.4
	0.3-0.6	5.6	0.25	2.25	18.9	380.0	758.2	157.2	99.7
	0.6-0.9	5.7	0.11	1.71	25.3	234.6	643.9	144.6	31.3
2	0-0.3	5.6	0.43	2.32	20.0	390.7	914.4	178.9	267.9
	0.3-0.6	5.2	0.22	1.81	5.0	343.5	676.8	164.5	108.8
	0.6-0.9	5.5	0.12	1.86	9.3	242.7	603.0	133.8	43.0
3	0-0.3	6.2	0.59	3.32	43.5	310.6	1876.7	326.8	341.7
	0.3-0.6	6.2	0.29	2.67	56.0	196.4	1428.3	242.2	88.9
	0.6-0.9	6.1	0.25	3.17	44.5	224.8	1614.7	282.9	87.0
4	0-0.3	6.1	0.69	5.93	187.2	775.0	2259.1	514.2	141.3
	0.3-0.6	6.3	0.40	7.46	64.9	698.5	3419.1	704.3	42.7
	0.6-0.9	7.1	0.28	8.03	11.2	499.0	4118.9	643.4	20.7
5	0-0.3	6.5	0.09	4.79	33.6	643.8	2047.6	510.9	17.9
	0.3-0.6	6.6	0.10	6.81	18.3	694.3	3051.0	716.0	12.0
	0.6-0.9	6.8	0.11	7.67	11.0	516.6	3219.3	484.2	3.6
6	0-0.3	5.6	0.50	2.54	161.5	414.1	1287.8	228.2	186.5
	0.3-0.6	5.3	0.38	2.49	59.2	358.0	1113.8	234.9	39.0
	0.6-0.9	5.3	0.79	8.15	21.2	918.5	3946.9	814.7	161.7

[a] Available P was converted to kg ha^{-1} from mg kg^{-1} using soil mass and density as described in the procedure
[b] Soil analysis of Ca and S includes substantial amounts of gypsum applied before soil sample collection, except for Field 5.

Soil mineral nutrient content before potato planting varied greatly among fields. Relatively high nutrient content was observed within the 0 – 0.3 m soil layer (Table 4-1 and 4-2), which could either be available for potato uptake or subjected to leaching loss to deeper layers. The relatively high initial soil nutrient content for all fields suggests a possible nutrient build-up as a result of continued fertilizer application over the years.

Table 4-2: Soil available phosphorus (P), exchangeable potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) and sulphur (S) content (mg kg^{-1}) measured in the top soil (0 – 0.3 m) layer for each field before potato planting.

	P	K	Ca	Mg	S
Field			mg kg^{-1}		
1	56.2	155.4	311.0	48.0	150.9
2	5.6	108.5	254.0	49.7	74.4
3	10.9	77.8	470.4	81.9	85.6
4	61.8	255.8	745.6	169.7	46.6
5	9.9	189.9	604.0	150.7	5.3
6	42.4	108.7	338.0	59.9	48.9

Soil available P observed in the 0 – 0.3 m soil layer ranged from 6 – 62 mg kg^{-1} for all fields (Table 4-2). Fields 2, 3 and 5 showed the lowest initial soil available P among all the fields. Soil P analysis (Bray 1 – P) less than 10 mg kg^{-1} (Fields 2, 3 and 5) is relatively low for potato production, whereas soil P analysis (Bray 1 – P) values greater than 30 mg kg^{-1} (Fields 1, 4 and 6) are relatively high (Steyn and Du Plessis 2012). According to fertilizer recommendations, Fields 2, 3 and 5 with low initial soil P may require P fertilization of between 150 – 200 kg ha^{-1} to obtain a potato yield target of 80 t ha^{-1}, whereas, Fields 1, 4 and 6 may require an additional P input of about 45 kg ha^{-1} to obtain the same target yield (Steyn and Du Plessis 2012). On average, all fields received 217 kg ha^{-1} P from inorganic fertilizers, which was quite close to the recommended P input rates (150 – 200 kg ha^{-1}) for soils with low initial P (Table 4-5).

Soil exchangeable K within the top 0 – 0.3 m soil layer ranged from 78 – 256 mg kg^{-1}, which falls under medium (70 – 150 mg kg^{-1}) to high (greater than 150 mg kg^{-1}) soil K levels for potato production (Steyn and Du Plessis 2012). According to fertilizer recommendations, soils with a CEC of less than 6 $cmol_c$ kg $^{-1}$ and K of between 70 – 150 mg kg^{-1} require K application of 190 – 250 kg ha^{-1} to obtain a yield of 80 t ha^{-1} (Steyn and Du Plessis 2012). On average, all fields received 309 kg ha^{-1} K from inorganic fertilizers, which was more than the recommended K rates of between 190 – 250 kg ha^{-1} under the stated soil CEC and initial soil K content for a target yield of 80 t ha^{-1} (Table 4-5). Field 4 showed the highest soil exchangeable K content of 256 mg kg^{-1}, followed by Field 5 with 190 mg kg^{-1}, within the 0 – 0.3 m soil layer (Table 4-2). This was because the two fields showed the highest CEC within the topsoil layer.

Very high soil exchangeable Ca and Mg levels were observed for all fields in the top 0 – 0.3 m soil layer, with a range of 311 – 746 mg kg^{-1} Ca and 48 – 170 mg kg^{-1} Mg (Table 4-2). Soil exchangeable Ca greater than 250 mg kg^{-1} and Mg concentration between 40 – 80 mg kg^{-1} are considered sufficient for potato (Steyn and Du Plessis 2012, Rosen 2018). Soil exchangeable Ca and Mg concentrations greater than 300 mg kg^{-1} and 100 mg kg^{-1}, respectively, are relatively high for potato production (Steyn and Du Plessis 2012, Rosen 2018). The very high Ca and Mg levels for all fields, except Fields 1 and 2, can be attributed to the presence of a chalky calcic hard pan layer at about 1 m depth in the soil profile. In addition, the growers usually apply high amounts of gypsum ($CaSO_4$), which probably resulted in soil profile Ca accumulation over the years of continuous cultivation. Fields 1 and 2 showed relatively lower Ca and Mg in the topsoil layer (0 – 0.3 m) as compared to the other fields (Table 4-2). This can be explained by the fact that no calcic hard pan layer was found in the top 1m of the profile for these fields, unlike the other fields where the chalky calcic layer was located close to the soil surface. For this reason, Ca and Mg contents were observed to increase with soil depth for Fields 3, 4, 5 and 6 (Table 4-1). Soil mineral S concentration within the 0 – 0.3 m soil layer ranged from 5 – 151 mg kg^{-1}. Soil with mineral S concentration greater than 12 mg kg^{-1} is relatively high for potato production (Rosen 2018). Field 5 with no history of crop cultivation showed the lowest mineral S content.

4.3.1.2 Fertilizer type, rate and method of application

The growers interviews revealed that NPK 7:15:7 (29) and gypsum as a source of Ca, were applied as a basal fertilizer broadcasted over the field, followed by a regular top-dressing of magnesium sulphate ($MgSO_4$), ammonium sulphate $(NH_4)_2SO_4$, calcium nitrate ($Ca(NO_3)_2$), potassium nitrate (KNO_3) and zinc sulphate ($ZnSO_4$) (Table 4-3). Micronutrient fertilizers such as Microsense® and boron Metalin® were applied in very low quantities, specifically to supply copper (Cu), manganese (Mn), boron (B), and zinc (Zn) to the potato crops. There was a close agreement between the average observed and recommended fertilizer application rate by the fertilizer company agronomist in the area (Table 4-3). This suggested that the growers followed the recommended rates in attempt to reduce production costs.

Table 4-3: Fertilizer type, average observed and recommended application rates for potato production in Louwna area.

Fertilizer type	Average observed application rate[a] (kg ha^{-1})	Recommended rate[b] (kg ha^{-1})
NPK 7:15:7 (29)	1375 (191)	1500
Vitacal/Unical	1360 (97)	1450
Magnesium sulphate ($MgSO_4$)	320 (112)	250
Ammonium sulphate $(NH_4)_2SO_4$	250	250
Calcium nitrate (Ca $(NO_3)_2$)	150	150
Potassium nitrate (KNO_3)	150	150
Zinc sulphate ($ZnSO_4$)	28.3 (5)	35

[a] Values in brackets represent standard deviation for all fields. Standard deviation was not calculated for fertilizer types applied at only one field.
[b] Recommended fertilizer rates by the local agronomist representing a fertilizer company for potato production in Louwna area.

4.3.1.3 Irrigation water quality

Irrigation water was also a significant source of mineral nutrients to the potatoes. Irrigation water chemical composition for each field is presented in Table 4-4. All fields were irrigated with groundwater from boreholes, and such water will contain mineral elements obtained from the parent rock as well as nutrients leached from topsoil layers. Irrigation water quality and chemical composition varied greatly among fields (Table 4-4). Irrigation water pH ranged from 7.9 – 8.3, which falls within the recommended irrigation water pH range of 6.5 – 8.4 as documented in the South African irrigation water quality guidelines (Department of Water Affairs and Forestry 1996). The EC varied from 0.34 – 0.93 mS cm^{-1}, with Fields 3 and 4 showing the highest values of 0.83 and 0.93 mS cm^{-1}, respectively. High irrigation water EC for Fields 3, 4 and 5 is attributed to elevated concentrations of Ca, Mg and S, suggesting the presence of dissolved salts like calcium carbonate, calcium sulphate and magnesium carbonate (Bauder et al. 2014). This is probably due to Ca and Mg dissolution, generated from weathering of the chalky calcic layer observed between 0.8 – 1 m soil depth for Fields 3, 4 and 5 (Soil Classification Working Group 2018). Fields 3 and 4 irrigation water also contained the highest nitrate N (NO_3-N), with values of 17.1 and 36.9 mg L^{-1}, respectively (Table 4-4). Consequently, irrigation water contributed significant amounts of N, Ca, Mg and S to the total nutrient input rates for all fields, except for Fields 1 and 2 (Table 4-5). This was probably because the calcic layer at Fields 1 and 2 was absent or much deeper than 1 m, showing little influence on the borehole water quality. Finally, irrigation water used for all fields showed low sodium (Na) levels relative to the sum of Ca and Mg concentration (Table 4-4), which implied low sodicity effects that usually reduce water infiltration into the soil (Bauder et al. 2014).

Table 4-4: The pH, electrical conductivity (EC), nitrate N (NO_3-N), hydrogen phosphate (H_2PO_4), potassium (K), calcium (Ca), magnesium (Mg), sulphate (SO_4) and sodium (Na) concentration of irrigation water used for potato production for each field.

Field	pH	EC (mS cm^{-1})	NO_3-N	H_2PO_4	K	Ca	Mg	SO_4	Na
			mg L^{-1}						
1	8.3	0.34	1.2	<0.75	<10	24.6	14.8	3.9	22.8
2	8.2	0.34	1.2	<0.75	<10	24.6	14.8	3.9	22.5
3	8.2	0.83	17.1	<0.75	<10	80.0	48.1	38.4	21.7
4	7.9	0.93	36.9	<0.75	<10	73.4	36.3	26.0	42.1
5	8.2	0.72	4.8	<0.75	<10	57.7	24.4	19.7	49.7
6	8.2	0.66	5.3	<0.75	<10	39.3	18.5	13.8	54.1

4.3.1.4 Nutrient input levels from inorganic fertilizers and irrigation water

Nutrient input levels of N, P, K, Ca, Mg and S from inorganic fertilizers and irrigation water are presented in Table 4-5. Inorganic fertilizers input rates of N, P K, Ca Mg and S were relatively similar for some fields, except for Field 6. Field 6 received considerably less of all nutrients, except P and S than all other fields. Average nutrient inputs from inorganic fertilizers were 276 kg ha^{-1} N, 217 kg ha^{-1} P, 309 kg ha^{-1} K, 136 kg ha^{-1} Ca, 17 kg ha^{-1} Mg and 47 kg ha^{-1} S. Nutrients inputs from irrigation water varied greatly among fields and ranged from 2 – 84 kg ha^{-1} N, 2 – 3 kg ha^{-1} P, 53 – 91 kg ha^{-1} K, 222 – 774 kg ha^{-1} Ca, 109 – 465 kg ha^{-1} Mg and 12 – 124 kg ha^{-1} S (Table 4-5).

Table 4-5: Nutrient input levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) from inorganic fertilizers and irrigation water applied for potato production for each field.

Field	Nutrient inputs (kg ha^{-1})					
	N	P	K	Ca*	Mg	S*
Inorganic fertilizer nutrients						
1	303.0	258.0	339.0	124.0	14.6	19.5
2	303.0	258.0	339.0	124.0	14.6	19.5
3	325.0	225.0	364.4	175.2	24.0	34.0
4	269.2	150.0	336.0	163.5	19.4	48.9
5	273.8	225.0	333.0	159.5	29.1	71.9
6	183.0	188.0	145.0	67.0	0.0	85.0
Average	**276.2**	**217.3**	**309.4**	**135.5**	**16.9**	**46.5**
Irrigation water nutrients						
1	2.4	3.0	81.5	223.0	133.7	11.85
2	2.4	3.0	81.0	221.5	132.8	11.79
3	37.4	3.2	87.0	773.6	465.0	123.7
4	84.2	3.3	91.0	742.5	366.8	87.45
5	8.9	2.7	74.0	473.9	200.6	53.95
6	7.7	1.9	53.0	231.9	109.2	27.1
Average	**23.8**	**2.8**	**77.9**	**444.4**	**234.7**	**52.6**
Total amounts						
1	305.4	261.0	420.5	347.0	148.3	31.4
2	305.4	261.0	420.0	345.5	147.4	31.3
3	362.4	228.2	451.4	948.8	489.0	157.7
4	353.4	153.3	427.0	906.0	386.2	136.3
5	282.7	227.7	407.0	633.4	229.7	125.8
6	190.7	189.9	198.0	298.9	109.2	112.1
Average	**300.0**	**220.2**	**387.3**	**579.9**	**251.6**	**99.1**

*Although Ca and S application rates appear low, substantial amounts of gypsum were applied before potato planting for all Fields, except for Field 5 and thus, Ca and S are reflected in the soil analysis (Table 4-1)

The N, P and K input rates observed in the present study are within the range of 142 – 373 kg ha^{-1} N, 36 – 214 kg ha^{-1} P and 96 – 510 kg ha^{-1} K reported for potato producing regions of South Africa (Steyn et al. 2016). Similarly, N, P and K input rates among potato growers in Zimbabwe ranged from 94 – 272 kg ha^{-1} N, 40 – 161 kg ha^{-1} P and 75 – 306 kg ha^{-1} K (Svubure et al. 2015). Sparrow (2012) reported that N, P and K median application rates in excess of 200 kg ha^{-1} N, 200 kg ha^{-1} P and 300 kg ha^{-1} K are used for potato producing regions of Tasmania, Australia. Nitrogen application rates between 150 – 250 kg ha^{-1} are used for potato production in north-western Europe (Vos 2009). Similarly, a 214 kg ha^{-1} N application rate is recommend for potato production in New Brunswick, Canada (Zebarth et al. 2004b). In contrast, N, P and K input rates lower than the ones observed in the present study have been used in the Netherlands with ranges 75 – 190 kg ha^{-1} N, 23 – 44 kg ha^{-1} P and 41 – 220 kg ha^{-1} K (Haverkort and Hillier 2011). The relatively low N, P and K input rates applied to potato in the Netherlands can be attributed to government restriction on nutrient use to minimize groundwater pollution. However, it is important to note that nutrient input rates are site-specific and mainly influenced by the soil type and its inherent fertility, potato cultivar, target yield and the climatic zone (Stark et al. 2004, Zebarth and Rosen 2007). For instance, relatively high N, P and K application rates are generally used in potato produced on sandy soils where nutrient loss risk through leaching is likely to be experienced (Steyn et al. 2016).

The observed large variation in total input levels of Ca, Mg and S among fields was mainly due to differences in irrigation water quality (Table 4-4). Fields 3 and 4 showed the highest total Ca input levels of 949 and 906 kg ha^{-1}, with the irrigation water contributing 81.5% and 81.9% of the total Ca, respectively (Table 4-5). The lowest Ca input rates of 347 and 345 kg ha^{-1} were observed for Fields 1 and 2, respectively. This was because the irrigation water of the two fields contained the lowest Ca concentration. Most soils generally contain enough Ca for adequate growth of most crops (Gunter and Palta 2008). Calcareous and alkaline soils as well as irrigation water can usually supply adequate Ca for potato growth (Gunter and Palta 2008). Nevertheless, research has shown that application of 168 kg ha^{-1} Ca effectively increased potato tuber Ca content, even on soils with pre-plant exchangeable Ca as high as 1,340 mg kg^{-1} (Gunter and Palta 2008). The Ca inorganic fertilizer input levels observed in the present study are within the range of 0 – 224 kg ha^{-1} reported in previous research studies (Ozgen et al. 2003, 2006, Karlsson et al. 2006, Gunter and Palta 2008). The excess Ca applied through irrigation water presented an increased risk of Ca leaching from potato fields.

On average the irrigation water contributed 91.5% of the total Mg input rates and 68.1% of the total S input rates for all fields. Similar to Ca, Fields 3 and 4 showed the highest total input rates for Mg, and S, with values of 489 and 386 kg ha^{-1} Mg, as well as 189 and 171 kg ha^{-1} S, respectively. Westermann (2005) documented that potato with a target yield of 56 t ha^{-1} removes approximately 63 kg ha^{-1} Mg and 22 kg ha^{-1} S, therefore, input rates close to total nutrient removal are recommended. Similarly, Mg and S amounts of 45 kg ha^{-1} Mg and 20 – 30 kg ha^{-1} S have been recommended for potato production with a target yield of 45 – 56 t ha^{-}

^{1} in Idaho, USA (Stark et al. 2004). Magnesium application rate of 100 kg ha^{-1} in potato has been investigated by Poberezny and Wszelaczyñska (2011), whereas S application rate of 50 kg ha^{-1} has been reported to improve potato tuber dry matter (Singh et al. 2016).

4.3.1.5 Correlation between total nutrient input rates and actual tuber yield

Total macro-nutrient input rates had a positive correlation with actual tuber yield, except for N (Table 4-6). Phosphorus input rates significantly correlated with actual tuber yield (Figure 4-1), whereas input rates of N and K correlations with actual tuber yield were not significant. This suggested that increasing macro-nutrient input rates for all fields might not result in increased actual tuber yield, except for P. This was probably due to a positive response to P fertilizer application, especially for Fields 2, 3 and 5 with relatively low initial soil P concentration (Table 4-2). Total nutrient input rates of Ca, Mg and S negatively correlated with actual tuber yield (Table 4-6). Generally, the correlations between most nutrient input rates and yield were not significant, which suggest that high nutrient application rates did not translate into increased tuber yield. Therefore, actual tuber yields of the present study could be obtained with lower nutrient application rates than the current nutrient rates used by the growers for all fields, except for Field 6 that applied less of all nutrients compared to the other fields (Figure 3-6).

Table 4-6: Correlation between total nutrient input levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) and actual tuber yield of all potato fields.

Nutrient input[1]	Correlation coefficient	*p*-Value
Total N	-0.079	0.8804
Total P	0.968	0.0015
Total K	0.229	0.6625
Total Ca	-0.411	0.4182
Total Mg	-0.342	0.5062
Total S	-0.468	0.3484

[1]Total nutrient input from inorganic fertilizer and irrigation water

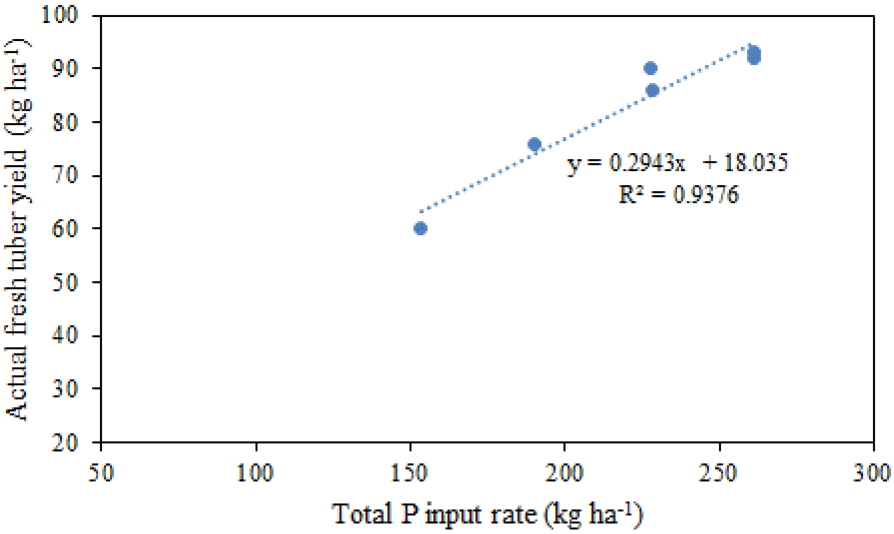


Figure 4-1: Positive correlation between total phosphorous (P) input rate and fresh tuber yield for all fields.

4.3.2 Potato nutrient outputs

4.3.2.1 Nutrient uptake and concentration in potato plant materials

Table 4-7 presents total nutrient uptake in tubers and aboveground parts (stems and leaves) of potato for each field. Results of this study agree with literature that potato takes up N and K in large amounts, while P, Ca, Mg and S are taken up in relatively smaller amounts (Beukema and van der Zaag 1990, Dean 1994, Westermann 2005, Govindakrishnan and Haverkort 2006). Nitrogen uptake in both tuber and aboveground parts varied greatly among fields. Tuber N uptake ranged from 181 – 364 kg ha^{-1}, while that of the aboveground parts ranged from 90 – 156 kg ha^{-1} (Table 4-7). Total potato N uptake observed in the present study was in line with the range of 2.3 – 5.9 kg N taken up by tubers and vines per ton of fresh tubers produced (Beukema and van der Zaag 1990, Dean 1994, Govindakrishnan and Haverkort 2006). Westermann (2005) documented that potato with a target yield of 56 t ha^{-1} takes up a total of 235 kg ha^{-1} N in Idaho, USA.

Table 4-7: Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) uptake of tubers and aboveground potato parts for each field.

Field	Nutrient uptake (kg ha^{-1})					
	N	P	K	Ca	Mg	S
Tuber uptake						
1	364.3	77.9	454.9	7.7	21.5	28.3
2	322.2	68.3	437.2	9.8	19.6	25.9
3	304.4	48.2	338.6	10.2	17.2	24.7
4	181.2	48.5	326.1	7.0	12.9	15.4
5	300.6	65.0	403.6	9.2	17.5	23.8
6	194.2	46.4	383.4	5.7	15.6	19.0
Average	**277.8**	**59.0**	**390.6**	**8.3**	**17.4**	**22.8**
Aboveground parts uptake						
1	147.9	12.8	219.8	119.7	51.8	17.4
2	156.3	11.8	224.8	190.2	69.0	16.5
3	147.4	10.7	186.3	154.9	85.2	15.3
4	90.3	8.1	149.0	64.7	28.7	10.3
5	152.6	14.2	228.2	120.5	49.9	17.1
6	120.0	10.6	192.5	111.9	42.5	14.3
Average	**135.8**	**11.4**	**200.1**	**127.0**	**54.5**	**15.2**
Total uptake						
1	512.2	90.7	674.7	127.4	73.3	45.7
2	478.5	80.1	662.0	200.0	88.6	42.4
3	451.8	58.9	524.9	165.1	102.4	40.0
4	271.5	56.6	475.1	71.7	41.6	25.7
5	453.2	79.2	631.8	129.7	67.4	40.9
6	314.2	57.0	575.9	117.6	58.1	33.3
Average	**413.6**	**70.4**	**590.7**	**135.3**	**71.9**	**38.0**

Tuber P uptake varied greatly between fields, with values ranging from 46 – 78 kg ha^{-1}, and an average value of 59 kg ha^{-1}. Phosphorous uptake by aboveground parts ranged from 8 – 14 kg ha^{-1} (Table 4-7). The total P uptake and removal observed in the present study falls within the range of 0.6 – 1.1 kg P taken up per ton of fresh tubers produced as reported by Dean (1994). Westermann (2005) reported that potato with a target yield of 56 t ha^{-1} removes 31 kg ha^{-1} P from the soil. Similarly, Stark et al. (2004) observed that potato requires 28 – 40 kg ha^{-1} of P to yield between 45 – 56 t ha^{-1}. The relatively high P uptake of the present study was probably due to high nutrient supply from soil and fertilizer sources, which resulted in luxurious P uptake of potato plant parts.

Potato tuber K content ranged from 326 – 455 kg ha^{-1} and that of aboveground plant parts ranged from 149 – 228 kg ha^{-1} (Table 4-7). Trehan et al. (2008a), Fernandes and Soratto (2016) and Girma (2017) documented that potatoes accumulate more K than N and P. The potato has rapid growth, a short development cycle and high yielding nature, so it requires significant K amounts for optimum growth and high tuber yield production (Stark et al. 2004, Trehan et al. 2008a, Alva et al. 2011, Banerjee et al. 2016, Fernandes and Soratto 2016, Girma 2017). For instance, K removed by both tubers and vines per ton of fresh tubers produced were reported to range from 7.1 – 10.7 kg t^{-1} (Dean 1994). This matched with the whole plant average K uptake of 7.1 kg t^{-1} obtained for all monitored fields of the present study (calculated from average total K uptake of 590.7 kg ha^{-1} and average tuber yield of 83 t ha^{-1}). Trehan et al. (2008a) stated that potato has a high response to K application in most soil types, and the crop tends to take up excess K amounts, resulting in a negative soil K balance after potato harvest. Accordingly, results of the present study suggested that a luxury K uptake and accumulation in both tubers and aboveground parts occurred.

Tuber Ca, Mg and S uptake ranged from 5.7 – 10.2 kg ha^{-1}, 12.9 – 21.5 kg ha^{-1}, and 15.4 – 28.3 kg ha^{-1}, respectively. The aboveground potato parts accumulated a range of 64.7 – 190.2 kg ha^{-1} Ca, 28.7 – 85.2 kg ha^{-1} Mg and 10.3 – 17.4 kg ha^{-1} S (Table 4-7). These results suggest that large amounts of the total Ca and Mg taken up by potato remains in the aboveground parts, therefore they are potentially recycled back into the soil. Nevertheless, the high nutrient uptake resulted in generally good tuber yields.

4.3.2.2 Nutrient leaching loss from potato

Although drainage and nutrient leaching were measured for four intensively monitored fields (Fields 1, 3, 4 and 6), it only occurred during the potato growing season in Field 1 (Figure 4-2 and Table 4-8). Field 1 had a sandy soil texture with very low water holding capacity, and no or rather deep chalky hard pan layer (located greater than 1 m depth) in the soil profile. In addition, Field 1 was irrigated with a relatively high total amount of 1040 mm, facilitating downward water and nutrient transport to deeper soil layers.

Cumulative nutrient leaching events for Field 1 showed that leaching was low early in the season and gradually increased until crop harvest. The highest nutrient leaching was recorded on 12 December 2017, corresponding to a heavy drainage event of about 100 mm that occurred between 23 – 24 November 2017, when the irrigation boom came to a standstill above the lysimeter (Figure 3-8).

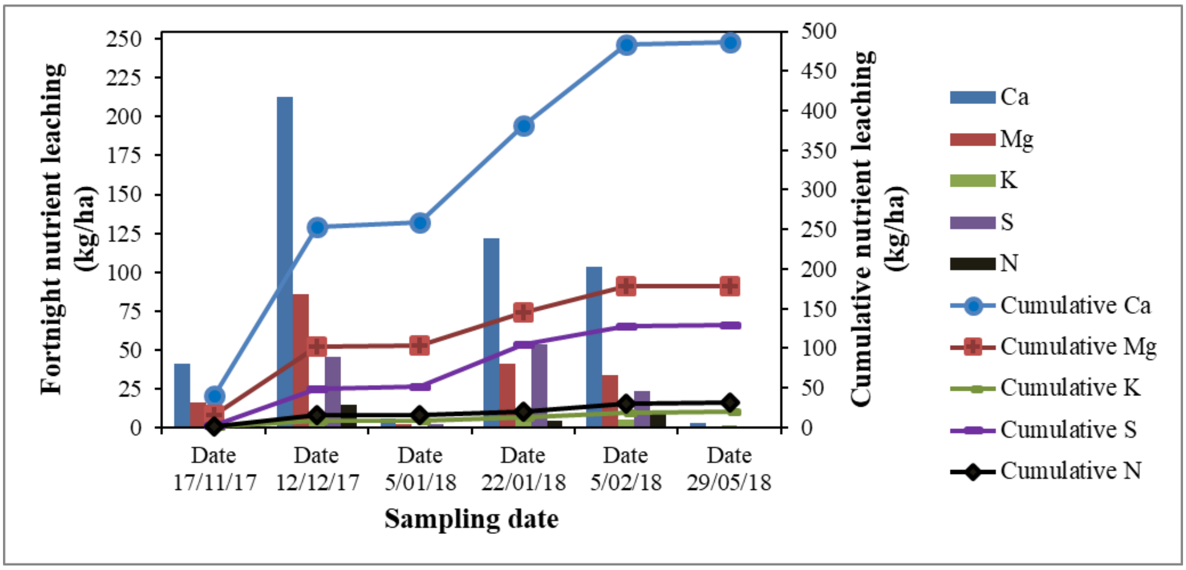


Figure 4-2: Fortnightly and cumulative nutrient leaching events during the October 2017 to February 2018 potato growing season for Field 1.

Total drainage of 488 mm was collected for Field 1, along with nutrient leaching of 29 kg ha^{-1} N, 20 kg ha^{-1} K, 484 kg ha^{-1} Ca, 179 kg ha^{-1} Mg and 129 kg ha^{-1} S (Table 4-8).

Table 4-8: Total drainage and nutrient leaching during the potato growing season of October 2017 to February 2018 for Field 1.

Field	Drainage (mm)	Nutrients leached (kg ha^{-1})					
		N	P	K	Ca	Mg	S
1	488	29	0	20	484	179	129

Previous studies mainly focused on N leaching from irrigated potato fields, with little attention paid to leaching of other nutrients such as P, K, Ca, Mg and S. For instance, nitrate (NO_3^-) leaching between 71 – 257 kg ha^{-1} was reported by Errebhi et al. (1998) from irrigated potato produced on sandy soil. Similarly, Prasad et al. (2015) reported N leaching of between 85 – 138 kg ha^{-1} from an irrigated potato field with sandy soils that received total N inputs ranging from 310 – 349 kg ha^{-1}. High Ca, Mg and S leaching were observed in the present study (Table 4-8). This may not be that the growers were over-fertilising, but because they do not take into account nutrient concentrations being added with the irrigation water.

Potassium K, Ca and Mg leaching loads observed in the present study fall within the ranges reported by Li et al. (2018), who obtained leaching of 8 – 55 kg ha^{-1} K, 100 – 600 kg ha^{-1} Ca and 50 – 200 kg ha^{-1} Mg from irrigated greenhouse cucumber (*Cucumis sativus* L.) grown over two seasons. Thompson (1991) observed total K, Ca and Mg leaching of 6, 358 and 237 kg ha^{-1}, respectively, in sugarcane over a three-year period (for plant crop, first and second ratoon crops) in Pongola, South Africa. There was no P leaching in the collected drainage water, probably because P has low mobility in the soil. On the contrary, average P leaching loads between 0.05 – 1.0 kg ha^{-1} were reported for a potato cropping system over a six-year study period in Sweden (Torstensson et al. 2006). Total P observed in the leachate collected in sugarcane from plant to second ratoon crops in Pongola, South Africa mounted to 0.3 kg ha^{-1} (Thompson 1991).

4.3.2.3 Soil mineral concentration before planting and after potato harvest

Comparison of soil available P, and exchangeable K^+ and Ca^{2+} before potato planting (initial) and after harvest (final) are illustrated in Figure 4-3. Relatively high soil P of 180, 187 and 162 kg ha^{-1} was observed in the 0 – 0.3 m soil layer for Fields 1, 4 and 6, respectively. On the contrary, Fields 2, 3 and 5 showed a low initial soil available P in the 0 – 0.3 m soil layer, with values of 20, 44 and 34 kg ha^{-1}, respectively (Figure 4-3a). The final soil P in the 0 – 0.3 m soil layer was similar to the initial soil P content for Felds 1, 4 and 6. Fields 2, 3 and 5 that previously had low initial soil P content, showed a substantial increase in the final soil available P (Figure 4-3b). This can be explained by the relatively higher P input rates used for Fields 2, 3 and 5, as compared to Fields 4 and 6 (Table 4-5).The large spike in final soil available P for Field 2 within the 0.3 – 0.6 m soil layer is difficult to explain, since P has a limited movement within the soil.

Soil exchangeable K^+ reflects the exchangeable soil colloid K fraction, which is highly dependent on clay content, CEC and soil organic matter (Alfaro et al. 2004, Essington 2015). Soil exchangeable K^+ before and after potato harvest decreased with soil depth for most fields (Figure 4-3 c and d). The highest initial soil exchangeable K^+ of 775 kg ha^{-1} in the 0 – 0.3 m soil layer was observed for Field 4, followed by 644 kg ha^{-1} for Filed 5 (Figure 4-3c). This was probably because Fields 4 and 5 have soils with the highest clay content (10 – 16%) within the profile. Conversely, Field 3 with relatively low clay content showed the lowest initial soil available K of 311 kg ha^{-1} in the 0 – 0.3 m soil layer. There was a slight decrease in final soil exchangeable K^+ content after potato harvest for all fields, except for Field 5. The slight decline in the final soil available K content was probably due to plant uptake, which was substantially more than the amounts applied (Tables 4-5 and 4-7). Field 6 showed a large reduction in final soil exchangeable K^+ content within the 0.6 – 0.9 m soil layer. This reduction in final K content is difficult to explain due to absence of measured drainage beyond the 0.9 m depth for this field.

Large soil exchangeable Ca^{2+} contents before planting and after potato harvest were observed for all fields (Figures 4-3 e and f). The large amounts of soil exchangeable Ca^{2+} was probably due to the influence of the calcic chalky layer in the profile, except for Fields 1 and 2 that had no calcic layer influence and had the sandiest soils. In addition, large Ca input rates from substantial gypsum application and irrigation water were applied by most growers during the season (Table 4-5). The Ca levels for all fields remained quite similar after potato harvest, except for Fields 5 and 6. Field 5 had quite low initial soil Ca content and showed an increase in final soil available Ca content, following a considerable Ca application with the irrigation water during the potato season (Figure 4-3 f). Similar to final exchangeable K for Field 6, a large reduction in soil exchangeable Ca content after potato harvest, especially within the 0.6 – 0.9 soil layer was observed.

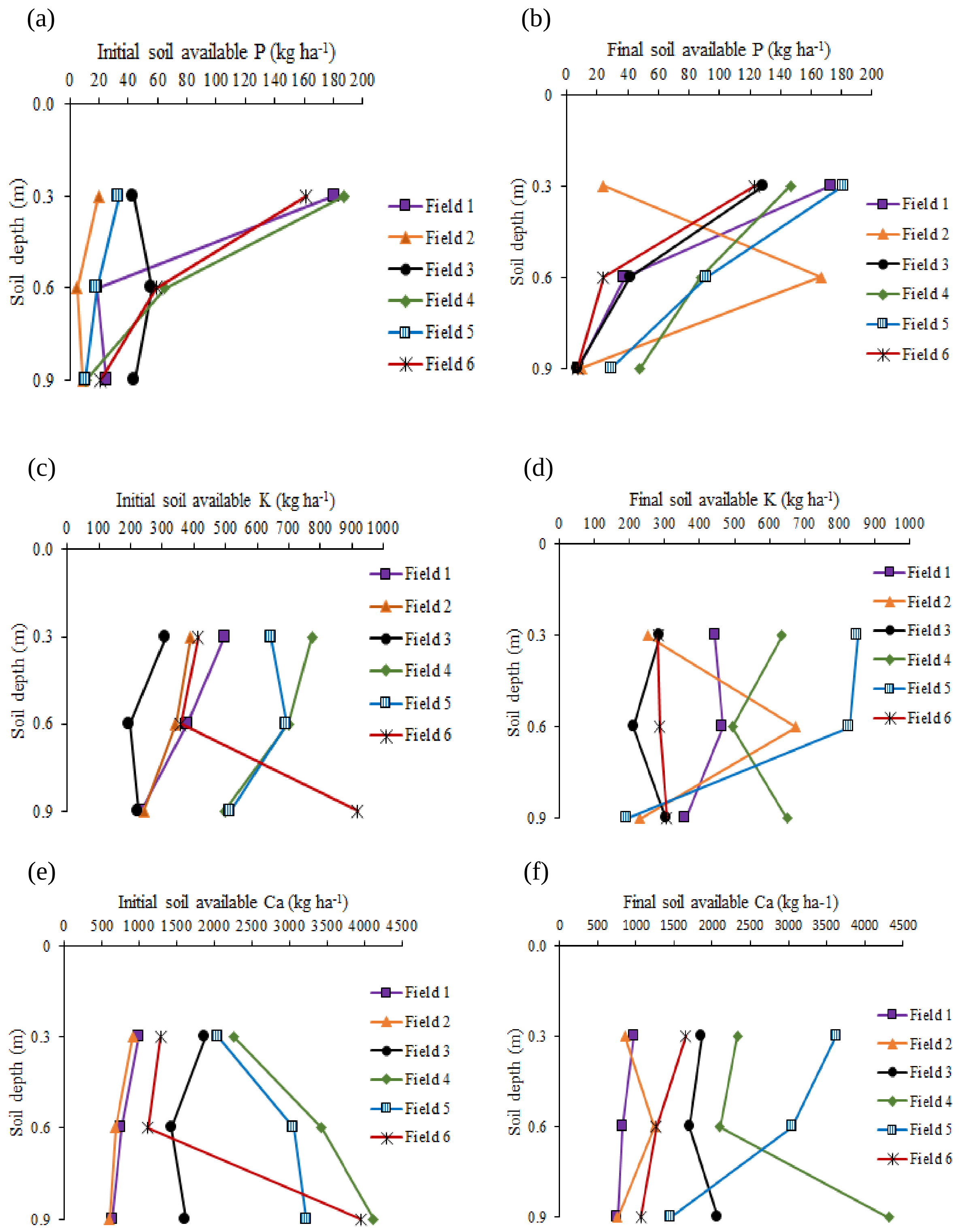


Figure 4-3: Soil profile initial soil available P (a), K (c), Ca (e) contents and final soil available P (b), K (d), and Ca (f) contents for the different fields before potato planting (initial) and after harvesting (final).

Figure 4-4 presents the soil exchangeable Mg^{2+} and soil mineral S contents before planting and after potato harvesting. Fields 4 and 5 showed the highest initial soil exchangeable Mg^{2+} levels in the entire profile, with values of 514 and 511 kg ha^{-1}, respectively, within the 0 – 0.3 m soil layer (Figure 4-4a). This was because Fields 4 and 5 had the highest clay content (10 – 16%), which has the capacity to retain cations (Mg^{2+}). In contrast, Fields 1 and 2 with low clay contents showed the lowest initial soil profile Mg levels, with values of 154 and 179 kg ha^{-1} within the 0 – 0.3 m soil layer, respectively (Figure 4-4a). There was a slight increase in the final soil available Mg within the profile for all fields, except for Field 6 (Figure 4-4b), which was probably due to large Mg input rates, mainly through irrigation water (Table 4-5). Similar to final exchangeable K and Ca, Field 6 showed a large reduction in final soil Mg within the 0.6 – 0.9 m layer.

There was no consistent trend between initial and final soil mineral S for all fields (Figure 4-4c and d). Soil mineral S declined over the potato season for Fields 1, 3 and 4, which may be due to potato plant uptake and S leaching to lowers layers. For instance, S leaching of 129 kg ha^{-1} observed for Field 1 (Table 4-8), was evidenced by a reduction in final soil S content of the 0 – 0.3 m soil layer, and an increase in S content within the 0.3 – 0.6 m and 0.6 – 0.9 m soil layers (Figure 4-4d). On the contrary, soil profile mineral S increased after the potato harvest for Fields 2, 5 and 6, with a sharp increase observed for Field 2 (Figures 4-4c and d). The substantial increase in soil profile S content for Field 2 was probably due to in-field variability and/or measurement errors, since for this field the lowest total S input from both inorganic fertilizer and irrigation water was applied. Fields 5 and 6, however, received relatively high S application rates, which probably resulted in high soil profile S after potato harvest (Table 4-5).

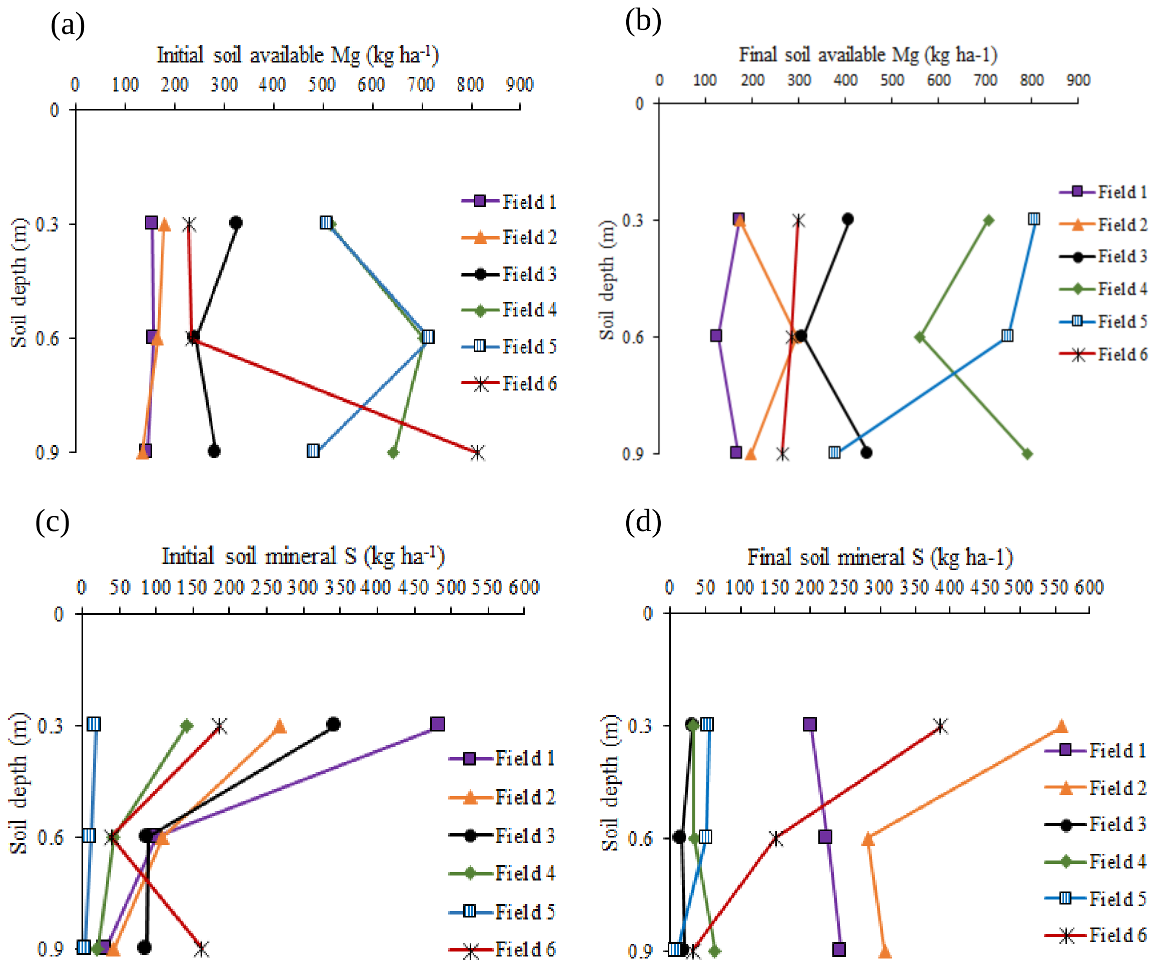


Figure 4-4: Soil profile initial available Mg (a), initial soil mineral S (c) and final soil available Mg (b) and final soil mineral S (d) contents for the different fields before potato planting (initial) and after potato harvest (final).

4.3.2.4 Partial nutrient balance

Partial nutrient balance (PNB) in potato production was determined for intensively monitored fields (Fields 1, 3, 4 and 6). This calculation excluded nutrients taken up in the aboveground plant parts of potato since they are left in the field after potato harvesting. Therefore, nutrient balance was the fertilizer proportion left in the soil as well as that accumulated in potato vines.

Table 4-9 presents PNB results corresponding to N, P, K, Ca, Mg and S. Partial nutrient balance of N (PNB_N) was negative for Fields 1 and 6, with values of -88 and -4 kg ha^{-1}, respectively.

Table 4-9: Total nutrient inputs (A), nutrient exports (B) (tubers and in-season leaching) and partial nutrient balance (C) of potato for the intensively monitored fields (Fields 1, 3, 4 and 6).

Nutrient	Field	Total nutrient input (A)	Nutrient exports (B)*		Partial nutrient Balance (C) = (A - B)
			Tubers	Leaching	
		kg ha^{-1}			
Nitrogen	1	305	364	29	-88
	3	362	304	0	58
	4	353	181	0	172
	6	191	194	0	-4
Phosphorus	1	261	78	0	183
	3	228	48	0	180
	4	153	49	0	105
	6	190	46	0	144
Potassium	1	421	455	20	-54
	3	451	339	0	113
	4	427	326	0	101
	6	198	383	0	-185
Calcium	1	347	8	484	-145
	3	949	10	0	939
	4	906	7	0	899
	6	299	6	0	293
Magnesium	1	148	22	179	-52
	3	489	17	0	472
	4	386	13	0	373
	6	109	16	0	93
Sulphur	1	31	28	129	-126
	3	158	25	0	133
	4	136	15	0	121
	6	112	19	0	93

*Exports excluding nutrients taken up in aboveground plant parts of potato, which are assumed to remain in the field after potato harvesting.

Fields 3 and 4 had a positive PNB_N, with values of 58 and 172 kg ha^{-1}. Partial nutrient balance of P (PNB_P) was positive for all intensively monitored fields with values ranging from 105 – 183 kg ha^{-1}. Partial nutrient balance for K (PNB_K) was negative for Fields 1 and 6, with values of -54 and -185 kg ha^{-1}, respectively, whereas positive PNB_K of 113 and 101 kg ha^{-1} was obtained for Fields 3 and 4, respectively (Table 4-9).

A negative PNB for Ca (PNB_{Ca}) of -145 kg ha^{-1} was obtained for Field 1, whereas positive PNB_{Ca} values of 939, 899 and 293 kg ha^{-1} were obtained for Fields 3, 4 and 6, respectively. Similarly, PNB for Mg (PNB_{Mg}) and PNB for S (PNB_S) were negative for Field 1, whereas Fields 3, 4 and 6 showed positive PNB_{Mg} and PNB_S (Table 4-9).

Partial nutrient balance of all nutrients was negative for Field 1, except for P (Table 4-9). This was because Field 1 had the highest nutrient tuber uptake and experienced nutrient leaching, which increased nutrient exports. Negative PNB_N and PNB_K observed for Field 6 were due to low nutrient input levels applied to potato for this field. The positive PNB_P was mainly due to very small P exports, since there was a small amount of harvested P in tubers and no leaching loss for all fields. Relatively large positive PNB_{Ca} and PNB_{Mg} recorded for Fields 3 and 4 were mainly due to large Ca and Mg inputs from irrigation water (Table 4-5). Positive PNB_S recorded for Fields 3, 4 and 6 were mainly due to relatively low S export through harvested tubers and the absence of S leaching in drainage water.

Negative PNB of the current study suggests larger nutrient export (through tuber harvest and leaching loss) as compared to nutrient inputs (from inorganic fertilizers plus irrigation water). Hence, the extra nutrients exported must have come from the soil reserve. On the contrary, a positive PNB suggest that a proportion of the nutrient inputs was left in the soil after potato harvest. Vos and Van der Putten (2000) reported average N balances after potato harvest of between 26 – 63 kg ha^{-1}, with average N input range of 213 – 250 kg ha^{-1} and N exports through tubers of 180 – 187 kg ha^{-1}. In the same study, P and K balances of 21 and -87 kg ha^{-1}, respectively, were obtained, with P and K inputs of 45 and 136 kg ha^{-1} and exports of 24 and 223 kg ha^{-1}, respectively (Vos and Van der Putten 2000). Likewise, Cambouris et al. (2008) reported average residual soil NO_3^- of 93 kg ha^{-1} within the top 0 – 0.7 m layer left after potato harvest, with N input rates ranging from 0 – 240 kg ha^{-1}. Residual soil NO_3^- of 160 kg ha^{-1} was measured within the 0 – 0.9 m depth soil profile in potato applied with 250 kg ha^{-1} N (Belanger et al. 2003). Therefore, results of the present and previous studies confirmed that potato leaves large amounts of soil residual nutrients, which may be prone to further post-harvest leaching losses.

4.3.3 Potato nutrient use efficiency

4.3.3.1 Partial factor productivity

Partial factor productivity (PFP) integrates soil indigenous and applied fertilizer nutrient contributions towards the overall tuber yield (Cassman et al. 1996, Ierna et al. 2011). Results corresponding to PFP for N (PFP_N), P (PFP_P), K (PFP_K), Ca (PFP_{Ca}), Mg (PFP_{Mg}) and S (PFP_S) are presented in Table 4-10. The PFP_N ranged from 170 – 399 kg tuber kg^{-1} N, with an average of 288 kg tuber kg^{-1} N. The lowest PFP_N of 170 kg tuber kg^{-1} N was observed for Field 4, which can be explained by the lowest actual tuber yield (60 t ha^{-1}) obtained at this field while N input was similar to that of other fields. The highest PFP_N of 399 kg tuber kg^{-1} N was recorded for Field 6, which was fertilized with the lowest N input. Fields 1, 2 and 5 showed PFP_N values above 300 kg tuber kg^{-1} N due to the high actual tuber yields of 90 – 93 kg ha^{-1}. Partial factor productivity of P (PFP_P) was relatively similar for all fields and values ranged from 352 – 400 kg tuber kg^{-1} P, with an average value of 379 kg tuber kg^{-1} P (Table 4-10). Conversely, PFP_K varied among fields as well as being lower than PFP_N and PFP_P. The PFP_K ranged from 141 – 384 kg tuber kg^{-1} K, with an average of 229 kg tuber kg^{-1} K. Field 4 showed the lowest PFP_K of 140 kg tuber kg^{-1} K and Field 6 with the highest value of 384 kg tuber kg^{-1} K (Table 4-9). Average PFP_{Ca}, PFP_{Mg} and PFP_S were 181 kg tuber kg^{-1} Ca, 445 kg tuber kg^{-1} Mg and 1381 kg tuber kg^{-1} S, respectively. Calcium had the lowest PFP_{Ca} compared with other nutrients for all fields, which suggest that relatively large Ca amounts were applied for each unit of the economic tuber yield produced. Sulphur showed the highest average PFP_S among all nutrients and values ranged from 440 – 2972 kg tuber kg^{-1} S. This was due to the relatively low S input levels used for all fields. Fields 1 and 2 had the highest PFP_S of 2934 and 2972 kg tuber kg^{-1} S, respectively, because the two fields were fertilized with the lowest S amount of 31 kg ha^{-1}.

Table 4-10: Partial factor productivity of N (PFP_N), P (PFP_P), K (PFP_K), Ca (PFP_{Ca}), Mg (PFP_{Mg}) and S (PFP_S) for each potato field as influenced by tuber yield and total nutrients applied.

Field	PFP_N (kg tuber kg^{-1} N)	PFP_P (kg tuber kg^{-1} P)	PFP_K (kg tuber kg^{-1} K)	PFP_{Ca} (kg tuber kg^{-1} Ca)	PFP_{Mg} (kg tuber kg^{-1} Mg)	PFP_S (kg tuber kg^{-1} S)
1	301.2	352.5	218.8	265.1	620.6	2934.2
2	304.5	356.4	221.4	269.2	631.2	2972.4
3	237.3	376.9	190.5	90.6	175.9	545.2
4	169.8	391.3	140.5	66.2	155.4	440.1
5	318.3	395.2	221.1	142.1	391.8	715.2
6	398.5	400.2	383.8	254.3	696.0	678.2
Average	**288.3**	**378.8**	**229.4**	**181.3**	**445.1**	**1380.9**

According to the definition used in the present study, PFP_N, PFP_P , and PFP_K results fall within the range of NUE values for potato production regions of South Africa reported earlier as 149 – 361 kg tuber kg^{-1} N, 147 – 465 kg tuber kg^{-1} P and 105 – 465 kg tuber kg^{-1} K (Steyn et al. 2016). The recalculated average PFP_N values for potato cultivars from North America was 398 kg tuber kg^{-1} N at 100 kg ha^{-1} N application rate (Zebarth et al. 2004b). Higher PFP_N, PFP_P and PFP_K values, however, were reported by Ierna et al. (2011), who obtained 519 kg tuber kg^{-1} N, 2377 kg tuber kg^{-1} P, 415 kg tuber kg^{-1} K for the lowest nutrient application rate of 50 kg ha^{-1} N, 11 kg ha^{-1} P and 63 kg ha^{-1} K (values recalculated from tuber yield, N, P, and K fertilizer application rate). Results of the present study indicated that high PFP can be obtained by maintaining relatively high tuber yields with reduced nutrient application rates. Similarly, previous studies have also showed that PFP decreased with increase in nutrient input rate (Ierna et al. 2011, Zhou et al. 2018).

4.3.3.2 Nutrient utilization efficiency

Nutrient utilization efficiency (NUtE) represents the ability of the crop to convert absorbed nutrients in DM or tuber yield (Sandaña 2016). This parameter depends on crop genotype, environment and crop management practices (Dobermann 2007). For this reason, it is often used to assess productivity and NUE of different crop genotypes (George et al. 2002, Wang et al. 2010, Sandaña 2016).

Nutrient utilization efficiency results of potato are presented in Table 4-11. Generally, average NUtE was highest for S with 584 kg DM kg^{-1} S uptake, while K showed the lowest average

NUtE of 37 kg DM kg^{-1} K uptake. The nutrient utilization efficiency of N ($NUtE_N$) was quite similar for all fields, ranging from 48 – 64 kg DM kg^{-1} N uptake, with an average of 54 kg DM kg^{-1} N uptake. The lowest $NUtE_N$ of 48 kg DM kg^{-1} N uptake was observed for Field 1, which had the highest total N uptake. The highest $NUtE_N$ of 64 kg DM kg^{-1} N uptake was observed for Field 6 following the lowest total N uptake for this field. Nutrient utilization efficiency of P ($NUtE_P$) for all fields was between 270 – 390 kg DM kg^{-1} P uptake, with an average of 318 kg DM kg^{-1} P uptake. Similar to $NUtE_N$, Field 1 showed the lowest $NUtE_P$ of 270 kg DM kg^{-1} P uptake, whereas, Field 6 had the highest $NUtE_P$ of 390 kg DM kg^{-1} P uptake. Nutrient utilization efficiency of K ($NUtE_K$) ranged from 34 – 44 kg DM kg^{-1} K uptake (average of 37 kg DM kg^{-1} K uptake). The lowest $NUtE_K$ of 34 kg DM kg^{-1} K was observed for Field 4, which can be attributed to the lowest DM produced for this field. The highest $NUtE_K$ of 44 kg DM kg^{-1} K was observed for Field 3, which had relatively high DM (22.9 t ha^{-1}) and second lowest K uptake (525 kg ha^{-1}) (Table 4-7). Nutrient utilization efficiencies of Ca ($NUtE_{Ca}$), Mg ($NUtE_{Mg}$) and S ($NUtE_S$) were relatively similar for all fields, with average values of 172, 321 and 584 kg DM kg^{-1} nutrient uptake, respectively. The lowest $NUtE_{Ca}$ and $NUtE_{Mg}$ of 124 and 280 kg DM kg^{-1} nutrient uptake, respectively, was observed for Field 2, which had the highest Ca (200 kg ha^{-1}) and second highest Mg (87 kg ha^{-1}) nutrient uptake (Table 4-7). Field 4 showed the highest $NUtE_{Ca}$, $NUtE_{Mg}$ and $NUtE_S$ of 223, 384, and 623 kg DM kg^{-1} nutrient uptake, respectively, which was due to the lowest total Ca, Mg and S uptake observed for this Field (Table 4-11).

Table 4-11: Nutrient utilization efficiency (NUtE) of nitrogen ($NUtE_N$), phosphorus ($NUtE_P$), potassium ($NUtE_K$), calcium ($NUtE_{Ca}$), magnesium ($NUtE_{Mg}$), sulphur ($NUtE_S$) as determined by potato total dry matter (DM) and nutrient uptake for each field.

Field	Total DM (t ha^{-1})	NUtE (kg DM kg^{-1} nutrient uptake)					
		$NUtE_N$	$NUtE_P$	$NUtE_K$	$NUtE_{Ca}$	$NUtE_{Mg}$	$NUtE_S$
1	24.5	47.9	270.4	36.4	192.6	334.9	536.6
2	24.8	51.8	309.7	37.5	124.0	280.0	584.3
3	22.9	50.8	389.6	43.7	138.9	223.9	574.0
4	16.0	58.9	282.8	33.7	223.1	384.4	622.9
5	24.0	53.0	303.0	38.0	185.1	356.2	586.5
6	19.9	63.5	350.0	34.6	169.7	343.5	599.2
Average	**22.0**	**54.3**	**317.6**	**37.3**	**172.2**	**320.5**	**583.9**

The average $NUtE_N$ of the present study was within the range of 54 – 111 kg DM kg^{-1} N uptake, which was observed by Zebarth et al. (2004b) for different commercial potato cultivars. In another study, average $NUtE_N$ of 97 kg DM kg^{-1} N uptake in potatoes was obtained at varying N application rates (Zebarth et al. 2004a). The $NUtE_P$ values for all fields fall within the range of 252 – 763 kg tuber DM yield kg^{-1} P uptake reported by Sandaña (2016). Dobermann (2007) documented that a very high NUtE may indicate a deficiency of that specific nutrient, whereas low NUtE indicates poor internal mineral conversion that can be due to factors such as nutrient deficiency, heat stress, salinity stress, pests and diseases. The very high $NUtE_S$ observed in the present study, however, was mainly because S is simply taken up in smaller quantities compared to other nutrients. The very low $NUtE_N$ and $NUtE_K$ were probably due to high potato N and K uptake observed for all fields (Table 4-7).

Nutrient utilization efficiency variations arise from differences in genotype, environment and crop management practices (George et al. 2002, Wang et al. 2010, Sandaña 2016). The growers investigated in the present study planted the same cultivar Mondial, except for Field 3, where cultivars Sifra and Lanorma were grown (Table 3-1). Thus, NUtE variations due to cultivar differences were probably very minimal. Similarly, the fact that potato was grown in the same agro-ecological zone, the effect of environmental variations on NUtE can also be considered as minimal. This leaves crop management practices and soil type as the main causes of NUtE variation among growers. Hence, appropriate crop management and manipulation of soil factors can result into increased NUtE of potato production.

4.3.3.3 Nutrient harvest index

Nutrient harvest index (NHI) quantifies the proportion of nutrients partitioned to tubers and is exported out of the field at harvest (Millard and Robinson 1990, Fageria 2014). Nutrient harvest index results for all fields are presented in Figure 4-5. Generally, the harvest index of a specific nutrient was quite similar for all fields (Figure 4-5). Phosphorus harvest index (NHI_P) was the highest, ranging from 81 – 86%, whereas calcium harvest index (NHI_{Ca}) was the lowest among all the nutrients and ranged from 5 – 10%. Nitrogen harvest index (NHI_N) ranged from 62 – 71%, and K harvest index (NHI_K) was between 64 – 69%. The Mg harvest index (NHI_{Mg}) was between 17 – 31%, with an average value of 25%. The S harvest index (NHI_S) ranged from 57 – 62%, with an average of 60%.

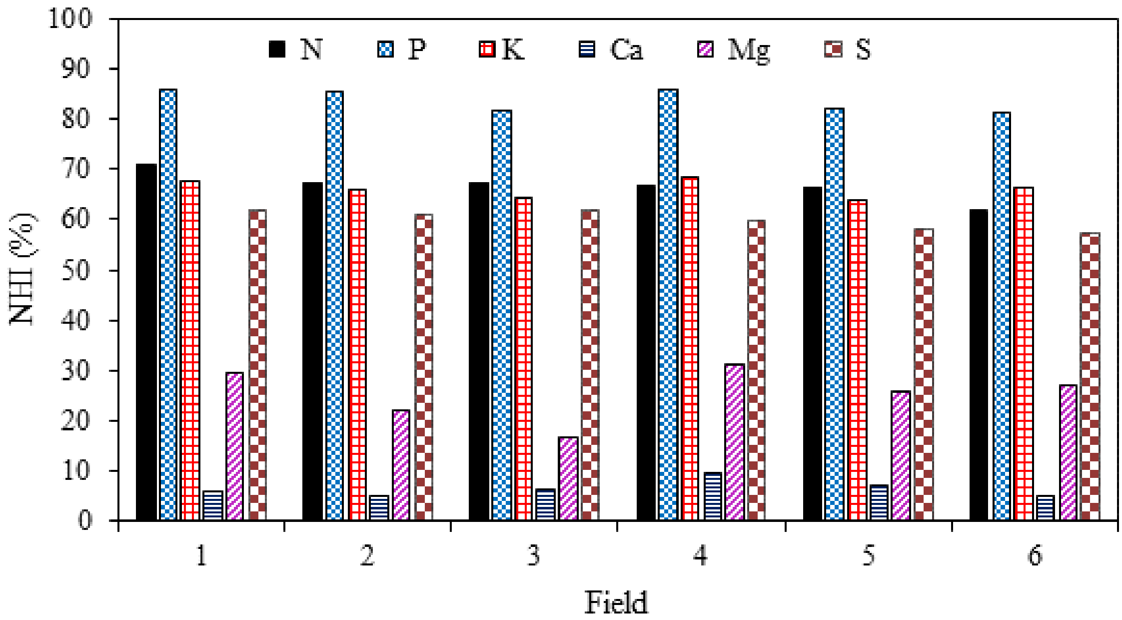


Figure 4-5: Nutrient harvest index (NHI) for potato as determined by tuber nutrient uptake at each Field.

The NHI_N values observed in the present study were within the range of 45 – 88% reported for different potato cultivars applied with 100 kg N ha^{-1} (Zebarth et al. 2004b). In the same study, the cultivar Mondial showed an average NHI_N of 47%, which was lower than the results of the present study. Likewise, Cambouris et al. (2008) reported tuber N recovery ranging from 19 – 65%, with N application rate between 0 – 240 kg ha^{-1}.

Phosphorous harvest index observed in the present study was close to the NHI_P range of 89 – 91% obtained by Rosen and Bierman (2008) at P application rates of 0, 37, 42 and 74 kg ha^{-1} (values recalculated from tuber P and the total P uptake). Nyiraneza et al. (2017) also reported NHI_P values of between 64 – 76% for Russet Burbank potato at P application rates ranging between 0 – 105 kg ha^{-1}.

Potassium harvest index averaged for all fields was 66%, corresponding with an average tuber K uptake of 391 kg ha^{-1}. These results were slightly higher than the average K amounts of 93 – 368 kg ha^{-1} removed by different potato cultivars that received K rates of between 0 – 330 kg ha^{-1} in England and Wales (Allison et al. 2001). A positive association between NHI and yield has been reported in grains, which implies that increased NHI results in high economic yield (Fageria 2014). High NHI_K (high tuber K accumulation), however, can lead to increased tuber water uptake, which reduces tuber specific gravity (Stark et al. 2004). Likewise, Allison et al. (2001) stated that increased tuber K uptake reduces tuber dry matter concentration, which negatively affect the quality of harvested potatoes. Therefore, it is important for potato growers to ensure optimal K supply for high quality tuber yield.

Calcium harvest index was very low, suggesting that 95 – 97% of total absorbed Ca remains in the aboveground plant parts. Calcium is a phloem immobile mineral element that is translocated along with transpiration water of plant tissues, therefore, plant organs such as tubers with low transpiration rate accumulate low Ca amounts (Taiz and Zeiger 2002, Westermann 2005). This explains the low NHI_{Ca} observed in the present study. Similarly, low tuber Ca content was reported by Clough (1994), with values ranging from 0.023 – 0.044% of dry weight with Ca application rate of 0 – 270 kg ha^{-1}. Magnesium harvest index was also quite low for all fields, implying that a high proportion of total Mg taken up remains in aboveground parts of potato plants. Sulphur harvest index suggested that tubers accumulate more than 60% of the total S taken up by the potato plant. Sulphur is important in tuber dry matter, starch and reducing sugar production (Trehan et al. 2008, Sharma et al. 2011, Singh et al. 2016). Overall NHI results suggest that potato tubers accumulate relatively large amounts of N, P, K and S. Like NUtE, NHI field differences were small, although amounts of nutrient inputs (fertilizer plus irrigation water) varied substantially between fields. Therefore, NHI was not affected by nutrient management practices of potato.

4.4 Conclusions

Generally, the growers applied large amounts of nutrients from inorganic fertilizers (knowingly) and with irrigation water (unknowingly) to potato crops. Nutrient input rates of potato varied greatly among fields, which was mainly due to differences in inorganic fertilizer rates, applied irrigation water volumes and mineral nutrient concentration of the water applied. Nutrient uptake results revealed that potato tubers remove large amounts of N and K, while P, Ca, Mg and S are taken up in relatively smaller amounts. Field 1 that had a sandy soil texture and without a drainage restricting chalky layer within the 0 – 1 m soil depth showed substantial drainage and nutrient leaching. A chalky layer at about 0.8 – 1 m depth probably restricted leaching for the other monitored fields. Hence, nutrient leaching presented the main source of variation in nutrient exports as well as partial nutrient balance among potato fields. Partial nutrient balance results indicated that large proportions of nutrients applied are left in the soil after potato harvest.

There was no consistent trend across the various NUE parameters of PFP, NUtE, and NHI for all fields. Partial factor productivity of all nutrients varied greatly between fields, which was due to substantial variations in tuber yields achieved and total nutrient amounts applied to potato. Nutrient utilization efficiency and NHI showed small field differences, although total amounts of applied nutrients varied greatly between fields. Therefore, NUtE and NHI parameters were probably not affected by nutrient management practices of potato, consequently, they are not ideal indicators for NUE estimation at field level. Partial factor productivity results for Field 6 revealed that NUE in potato production can be increased by maintaining relatively high tuber yields with reduced nutrient input rates. Hence, potato growers should determine nutrient input rates based on initial soil and irrigation water nutrient analysis to reduce excessive nutrient addition, which in turn increases NUE and reduce nutrient loss through leaching.

CHAPTER 5

EFFECT OF NUTRIENTS CARRIED-OVER AFTER POTATO HARVEST ON YIELD, WATER AND NUTRIENT USE EFFICIENCY OF SUBSEQUENT CROPS

5.1 Introduction

Application of large amounts of fertilizer is a common practice in irrigated potato (*Solanum tuberosum* L.) grown on sandy soils. Moreover, potato is inefficient at recovering nutrients from the soil, mainly due to its relatively shallow root system. As a result, large amounts of nutrient are left in the soil after potato harvest (Webb et al. 2000, Delgado et al. 2001, Munoz et al. 2005, Aguilera et al. 2014).

The amount of nutrients left in the soil depends on fertilizer type, rate and time of application, tuber yield, crop residue management, rainfall amount and distribution, irrigation management, irrigation water quality and soil type (Aguilera et al. 2014). For instance, fertilizer applied after the tuber bulking stage or close to crop senescence might not be taken up by the crop, which may result in increased soil residual nutrients after potato harvest (Zotarelli et al. 2015). Also, haulm mineralization adds mineral nutrients into the soil, leading to increase in left-over nutrients after potato harvest. Soil properties in terms of organic matter content, clay content and cation exchange capacity (CEC) influence mineral nutrient retention into the soil, as well as nutrient loss through leaching (Aguilera et al. 2014).

Nutrients not recovered by the potato crop may be leached to deeper soil layers, particularly in the presence of heavy rainfall and irrigation events (Zotarelli et al. 2015). Leached nutrients to deeper soil layers can, however, still be recovered by a relatively deep-rooted crop planted in rotation with potato (Delgado et al. 2001, Munoz et al. 2005, Aguilera et al. 2014). Nutrient dynamics in potato rotation with crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), spring wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.) and oats (*Avena sativa* L.) have been widely studied (Porter and Sisson 1991, Vos and Van der Putten 2000, Webb et al. 2000, Davenport et al. 2005, Swain et al. 2014). A crop following potato can enhance overall nutrient recovery and minimize nutrient loss and groundwater contamination through leaching (Vos and Van der Putten 2000, Vos and Van der Putten 2004, Munoz et al. 2005, Jiang et al. 2012).

South African potato growers sometimes plant a follow-up crop (subsequent crop) after harvesting potatoes. In these potato-based rotation systems, shallow to moderately deep-rooted crops such as groundnuts (*Arachis hypogaea* L.), paprika pepper (*Capsicum annuum* L.), onions (*Allium cepa* L.), maize (*Zea mays* L.) and pasture grass are planted after the potato harvest. The effect of nutrients carried-over after potato on subsequent crop growth and the overall rotation system nutrient use efficiency (NUE), however, is not well understood locally. Therefore, this study was carried out to evaluate nutrient carry-over effect on subsequent crop yield, WUEs and NUEs. This was achieved through on-farm detailed measurement of water and nutrient input rates, nutrient uptake, crop yield, and drainage and nutrient leaching of the subsequent crop. The collected data was also used to estimate the overall soil nutrient balance of potato-based rotation systems on selected fields.

5.2 Materials and methods

5.2.1 Subsequent crop monitoring

Four of the six fields previously planted with potato were monitored during the subsequent crop season (Refer to Chapter 3: Table 3-2). Monitored fields included: Fields 1, 3, 4 and 5. Fields 2 and 6 were not monitored because no subsequent crop was planted on these fields. Table 5-1 shows fallow period, subsequent crop type, planting and harvest dates for Fields 1, 3, 4 and 5. Growers themselves selected the subsequent crop following potato harvest (Table 5-1). Fallow periods between potato harvest and subsequent crop planting date varied between growers as presented in Table 5-1.

After potato harvesting, Fields 3, 4 and 5 were planted with paprika pepper, groundnuts and onions, respectively. Field 1 was planted with bottle brush pasture grass (*Anthephora pubescens*) that did not establish well; therefore, this field was considered to be under fallow throughout the monitoring period. Growers followed their own crop management practices related to cultivation, soil preparation, crop and cultivar choice, planting, tillage, irrigation scheduling, fertilizer application, as well as weed, pest and disease control. The concept was to monitor water and nutrient use of the subsequent crops after potato harvest at field level without interfering with the farm activities.

Table 5-1: Fallow period, crop type, planting and harvest dates of the subsequent crops planted after the potato crop for Fields 1, 3, 4 and 5.

Field	Fallow period	Subsequent crop	Planting date	Harvest date
1	05/02/18 - 06/05/19	Pasture/Fallow	-	-
3	30/01/18 -15/10/18	Paprika	16/10/2018	10/05/2019
4	30/01/18 - 19/11/18	Groundnuts	20/11/2018	06/05/2019
5	20/02/18 - 06/05/18	Onion*	07/05/2018	07/11/2018

*This field was not intensively monitored.

5.2.2 Data collection and equipment installation

Subsequent crops were monitored in the same manner and with the same equipment as for potato as reported in Chapter 3.

5.2.3 Weather data collection

Weather variables such as rainfall, daily maximum and minimum temperature, solar radiation and wind speed were recorded by automatic weather stations (AWS) installed at Fields 1 and 3 at the start of the potato season.

5.2.4 Irrigation water quality, total water and nutrient input levels

Irrigation amount and water quality applied to the subsequent crop for each field were determined following the procedure as described in Chapter 3. Total water inputs were determined from the sum of irrigation amounts and rainfall amounts received during the fallow and subsequent crop growth periods. Total amounts of nutrient inputs were determined as the sum of inorganic fertilizers and nutrients applied with irrigation water of each subsequent crop.

5.2.5 Estimation of crop evapotranspiration

Crop evapotranspiration (ET_c) was estimated from the product of a crop coefficient (Kc) and the ET_o according to the method recommended by Allen et al. (1998) (Equation 5.1).

$$ET_c = Kc \times ET_o \quad (5.1).$$

Crop coefficient values for the initial (Kc_{in}), mid-season (Kc_{ms}) and late-season (Kc_{ls}) stages for paprika, groundnuts and onions are presented in Table 5.2

Table 5-2: Crop coefficient values for the initial (Kc_{in}), mid-season (Kc_{ms}) and late-season (Kc_{ls}) growth stages for paprika, groundnuts and onions (Allen et al. 1998).

Crop	Kc_{in}	Kc_{ms}	Kc_{ls}
Paprika	0.6	1.05	0.9
Groundnuts	0.4	1.15	0.6
Onion	0.7	1.05	0.75

The length of each growth stage of paprika, groundnuts and onion that was used to select the respective Kc value is presented in Table 5-3.

Table 5-3: Length of crop development stages for paprika, groundnuts and onions (Estimated from values reported in Allen et al. 1998).

Crop	Initial stage (days)	Development + mid-season stages (days)	Late-season stage (days)	Total (days)
Paprika	30	150	23	203
Groundnuts	25	108	35	168
Onion	20	128	40	188

5.2.6 Soil sampling

Initial soil sampling before subsequent crop planting was done after potato harvest, whereas final soil sample collection was carried out at the respective subsequent crop harvest. For soil sampling and analysis procedure, refer to Chapter 3.

5.2.7 Plant material sampling and nutrient analysis

Whole plant samples of paprika peppers, groundnuts and onions were collected from Fields 3, 4 and 5, respectively. Representative plant samples were obtained from each quarter of the centre-pivot. Four randomly selected sites of 1 m^2 were sampled per quarter to form a composite sample for the entire field. The plants were separated into leaves, stems, fruits or pods or bulbs and thereafter weighed to obtain fresh mass. Separated plant parts were washed with running tap water, sliced and dried in an oven with forced air circulation at 60 °C until constant dry mass. The dried samples were then weighed to obtain dry matter (DM) yields. Dried plant samples were sent to Nvirotek Laboratory for standard nutrient status analysis. Total nitrogen (N) was analysed using the Dumas method that involves dry combustion of all N constituents in an automated LECO CHN 600 machine (Simonne et al. 1997). The elements phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) were analysed using Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) after acid digestion of the samples using nitric acid (Hou and Jones 2000). Plant nutrient uptake was calculated by multiplying the whole plant nutrient concentration by the total dry matter accumulation.

5.2.8 Subsequent crop yield measurement

Paprika pepper yield was determined from the DM content of fruit samples collected from 1 m^2 area in each quarter segment of the field. Similarly, groundnut yield was determined by calculating the average DM of pods collected from 1 m^2 area in each quarter segment of the field. Weighed groundnut pod samples were de-shelled to determine dry grain yield (10% moisture content) and the shell mass fraction. Onion plant samples taken from 1 m^2 area of each quarter segment of the field were used to determine fresh and dry onion bulb yields. Calculated yields for the three fields were compared with final yields obtained by the respective growers.

5.2.9 Drainage water sampling and nutrient analysis

Drainage water from Fields 1, 3 and 4 was collected using Decagon G3 drainage lysimeter (DL) as described in Chapter 3. Drainage water sampling started after potato harvest until the subsequent crop harvest, with the samples collected at a fortnight interval. Drainage and nutrient leaching during the fallow and the subsequent crop growth periods were monitored. Drainage was recorded at each sampling date and a representative water sample was analysed for nutrient concentration. The amount of leached nutrients in drainage water was determined as described in Chapter 3.

5.2.10 Water and nutrient use efficiency of the subsequent crop

Paprika water use efficiency (WUE_{R+I}) (kg mm^{-1}) was defined as the ratio of fruit dry matter yield to the total amount of water applied (mm ha^{-1}). Groundnut WUE_{R+I} (kg mm^{-1}) was defined as the ratio of fresh pod yield (kg ha^{-1}) to the total amount of water applied (mm ha^{-1}). Onion WUE_{R+I} (kg mm^{-1}) was defined as the ratio of fresh onion bulb yield (kg ha^{-1}) to the total amount of water applied (mm ha^{-1}). These parameters were calculated using Equations 5.2 – 5.4.

$$\text{Paprika pepper } WUE_{R+I} = \frac{\text{Fruit dry matter Yield}}{\text{Rainfall+irrigation}} \quad (5.2)$$

$$\text{Groundnut } WUE_{R+I} = \frac{\text{Dry grain Yield}}{\text{Rainfall+irrigation}} \quad (5.3)$$

$$\text{Onion } WUE_{R+I} = \frac{\text{Fresh onion bulb Yield}}{\text{Rainfall+irrigation}} \quad (5.4)$$

Nutrient use efficiencies of paprika, groundnuts and onions were analysed using partial factor productivity (PFP) and nutrient harvest index (NHI) using Equations 5.5 – 5.6.

$$\text{PFP} = \frac{\text{Subsequent crop economic yield}}{\text{Nutrient applied}} \quad (5.5)$$

where subsequent crop economic yield (kg ha^{-1}) refers to: paprika dry fruit yield or groundnut dry grain yield or onion fresh bulb yield. Nutrient applied (kg ha^{-1}) from inorganic fertilizers and irrigation water

$$\text{NHI} = \frac{N_t}{N_u} \times 100 \quad (5.6)$$

where NHI (%), Nt (kg ha^{-1}) is nutrient taken up in subsequent crop economic product (Paprika fruit yield, groundnut dry grain yield and onion fresh bulb) and N_u (kg ha^{-1}) is whole plant nutrient uptake.

5.2.11 Overall potato - based rotation system partial nutrient balance

Overall potato-based rotation partial nutrient balance (PNB, kg ha^{-1}) was defined as the difference between total potato rotation nutrient inputs (kg ha^{-1}) and total nutrient exports (kg ha^{-1}) during the potato season, fallow period and subsequent crops. Total nutrient inputs consisted of the sum of nutrient inputs to potato and the subsequent crop. Total potato rotation nutrient exports included the nutrient amounts in harvested plant products of potato tubers, paprika fruits, groundnut pods and onion bulbs, and nutrient losses through leaching during the potato crop, fallow period and the subsequent crop seasons (Tesfamariam et al. 2009). This was calculated using Equation 5.7.

$$\text{PNB} = [(\text{nutrient input}) - (\text{nutrient output})] \quad (5.7)$$

e.g. Total PNB of N = [(N inputs to potato + N inputs to follow-up crop) – (N in harvested tubers + N in harvested parts of follow-up crop + leached N in potato, fallow period and follow-up crop)].

5.3 Results and discussion

5.3.1 Weather data

Weather conditions during the fallow period and subsequent crop periods are presented in Table 5-4. Daily average maximum air temperature ranged from 19 – 35 ^{o}C, and temperatures regularly exceeded 30 ^{o}C between November 2018 and January 2019. Daily average air minimum temperatures ranged from 0 – 17 ^{o}C, with the coldest nights occurring between May and September 2018. Temperature influenced paprika and groundnut planting dates since the two crops require relatively high soil temperatures for germination (Table 5-1). Daily average solar radiation lower than 20 MJ m^{-2} d^{-1} was recorded between March and September 2018 corresponding to the winter period (Table 5-4). Very low rainfall was recorded during the subsequent cropping season (May 2018 to April 2019). The maximum monthly total ET_o was recorded during the hottest months, between November 2018 and January 2019, which corresponded to the paprika and groundnut cropping seasons.

Table 5-4: Louwna daily average maximum and minimum temperature, daily average radiation, monthly total rainfall and monthly total reference evapotranspiration (ET_o) measured during the fallow period and during the subsequent crop seasons from March 2018 to April 2019.

Month	Daily average maximum temperature (ºC)	Daily average minimum temperature (ºC)	Daily average radiation (MJ m^{-2} d^{-1})	Monthly total rainfall (mm)	Monthly total ET_o (mm)
			2018		
March	29.8	13.5	19.8	113	138
April	27.6	11.6	13.4	152	78
May	23.8	4.6	14.2	3	94
June	22.0	0.4	13.2	2	82
July	19.4	0.3	13.6	9	80
August	23.8	2.5	16.0	0	129
September	27.8	4.3	19.8	0	165
October	29.9	10.0	23.7	5	187
November	32.4	12.3	27.1	10	222
December	34.9	15.8	27.2	12	258
			2019		
January	35.6	16.6	27.3	16	252
February	32.5	16.1	22.6	67	169
March	33.5	14.4	20.6	40	171
April	26.6	11.0	15.1	196	106

5.3.2 Water and nutrient inputs to the subsequent crops

5.3.2.1 Total water input levels and irrigation water quality

5.3.2.1.1 Total water input volumes

Water inputs through irrigation and rainfall are presented in Figure 5-1. Field 1 was not irrigated since it was under fallow after the potato harvest, however, a total of 621 mm of rainfall was recorded from March 2018 to April 2019. Field 3 that was planted with paprika received the highest total water inputs of 1526 mm, with irrigation contributing 78% of the total amount (Figure 5-1). Field 4 was planted with groundnuts and received a total water input of 1134 mm, where irrigation contributed 71% of the total water amount. The onions were planted in Field 5 and received the least amount of irrigation (789 mm) and rainfall of 16 mm (Figure 5-1).

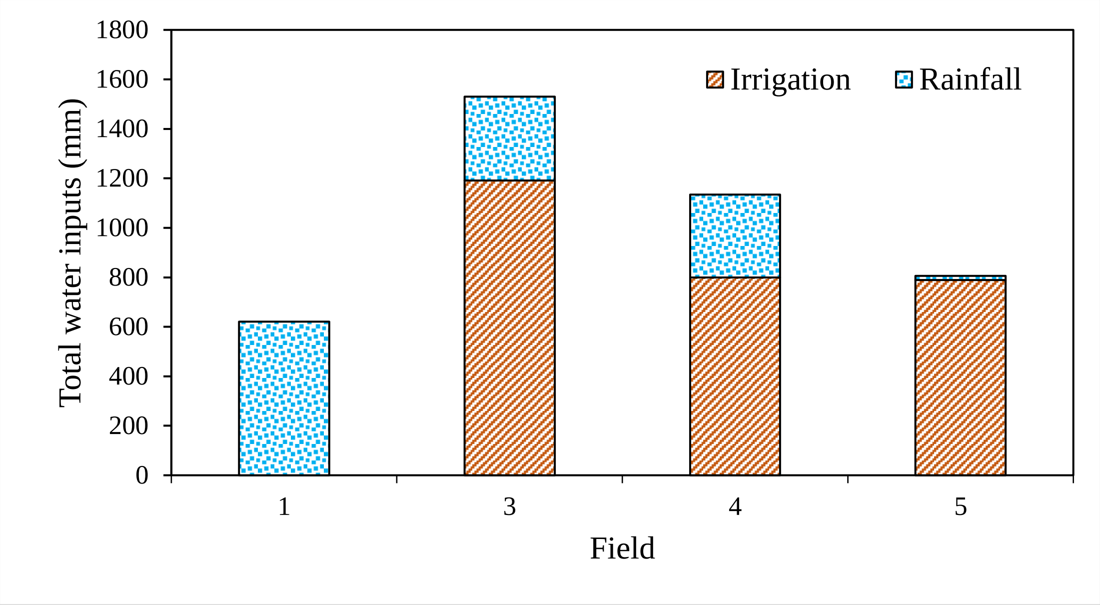


Figure 5-1: Subsequent crop water inputs through irrigation and rainfall for Fields 1, 3, 4 and 5 recorded during the respective cropping seasons.

Water application through irrigation and rainfall is essential in paprika pepper production since the crop is highly sensitive to water stress (Sezen et al. 2006, Gonzalez-Dugo et al. 2007, Kirnak et al. 2016). Water stress affects plant leaf area, fruit weight and delays fruit ripening, which substantially lower paprika economic yield and quality that is dependent on fruit flavour and colour (Gonzalez-Dugo et al. 2007, Shongwe et al. 2010). Irrigation of 1192 mm applied to paprika in the present study was far higher than the recommended 874 mm irrigation for paprika pepper production in Turkey, as determined by an irrigation scheduling computer program based on weather conditions of the season (Kirnak et al. 2016). Similarly, irrigation water applications ranging from 346 – 480 mm have been used for paprika production in Cordoba, Spain during the summer season (Gonzalez-Dugo et al. 2007).

Although groundnuts are a fairly drought tolerant crop, it is also affected by water stress that leads to reduced biomass production and pod yield (Reddy et al. 2003, Mandal et al. 2019). Therefore, irrigation is necessary to supplement the low and irregular rainfall that is usually received during the dry and hot summer cropping season. Total water input to groundnuts of 1134 mm for Field 4 was far higher than the average total water inputs of 354, 403 and 471 mm that were applied to rainfed, deficit and optimally irrigated groundnuts trials, respectively, in the KwaZulu-Natal province of SA (Chibarabada et al. 2019). In the same experiment, the measured crop water use (evapotranspiration) was 283, 292 and 319 mm for rainfed, deficit and optimally irrigated groundnuts, respectively (Chibarabada et al. 2019). Total water inputs ranging from 353 – 547 mm have been applied to groundnuts produced during the summer season in India (Bandyopadhyay et al. 2005). Haro et al. (2008), reported average cumulative water use of 478 and 677 mm for water stressed and fully irrigated groundnuts, respectively, grown over two growing seasons in Argentina. However, comparison of water inputs of groundnuts between production areas is difficult due to variations in weather conditions and water availability during the season.

Onion has a shallow root system, which makes it highly sensitive to water stress. Therefore, frequent water supply through irrigation is required to maintain adequate root zone soil water (Kumar et al. 2007). Irrigation water applied to onion in Field 5 amounted to 789 mm. This compares well to seasonal water inputs of between 400 – 700 mm applied to onion in similar dry areas of northern Nigeria (Igbadun et al. 2012). Average irrigation of 342 mm was applied to onion when the average crop evapotranspiration of 335 mm was recorded during the winter/summer season in Punjab, India (Kumar et al. 2007). In the same way, total water supply of 472 and 549 mm were applied to onion grown in Lower Rio Grande Valley of Texas, United States of America (USA) (Enciso et al. 2007). While the risks of over-irrigation are present, especially for Field 3, it should be noted that the centre pivots used had an average application efficiency of 85%, implying that 15% of the total water applied can be lost to the air during irrigation, direct evaporation from foliage and deep percolation.

5.3.2.1.2 Comparison between water inputs and estimated crop evapotranspiration

Crop ET is important to estimate crop water requirements during the season (Allen et al. 1998). Comparison between water inputs and the amount of water lost through ET provides a clear reflection of over- or under-irrigation, which can either lead to drainage or crop water stress. The daily rain plus irrigation, calculated daily ET_c, cumulative rain plus irrigation and cumulative ET_c for Field 3 (paprika), Field 4 (groundnuts) and Field 5 (onion) are presented in Figure 5-2. Daily irrigation was higher than the daily ET_c for most months of the paprika season (Figure 5-2a). Consequently, the cumulative rain plus irrigation (1526 mm) exceeded the cumulative ET_c (1239 mm) (Figure 5-2a). This suggests that Field 3 received excess water, which presented a risk of drainage and nutrient leaching from the paprika field.

In Field 4 daily water inputs, mainly through irrigation, generally did not exceed daily ET_c for most of the days during the groundnut season (Figure 5-2b). Consequently, the cumulative ET_c was higher than cumulative rain plus irrigation for most of the season. This may suggest that the groundnuts suffered from water stress during the growing season. However, substantial rainfall received during the last month of the growing season (April 2019) led to cumulative total water inputs to exceed cumulative ET_c, which presented a risk of drainage (or waterlogging due to restricting layer) for Field 4 at the end of the crop season (Figure 5-2b).

Daily rain and irrigation figures were generally close to daily ET_c for Field 5 during the entire onion season. Therefore, the cumulative rain plus irrigation (805 mm) was close to cumulative ETo (765 mm) (Figure 5-2c). This suggests that the grower applied irrigation accurately according to onion crop ET, which most likely minimised the risk of drainage and nutrient leaching for this field.

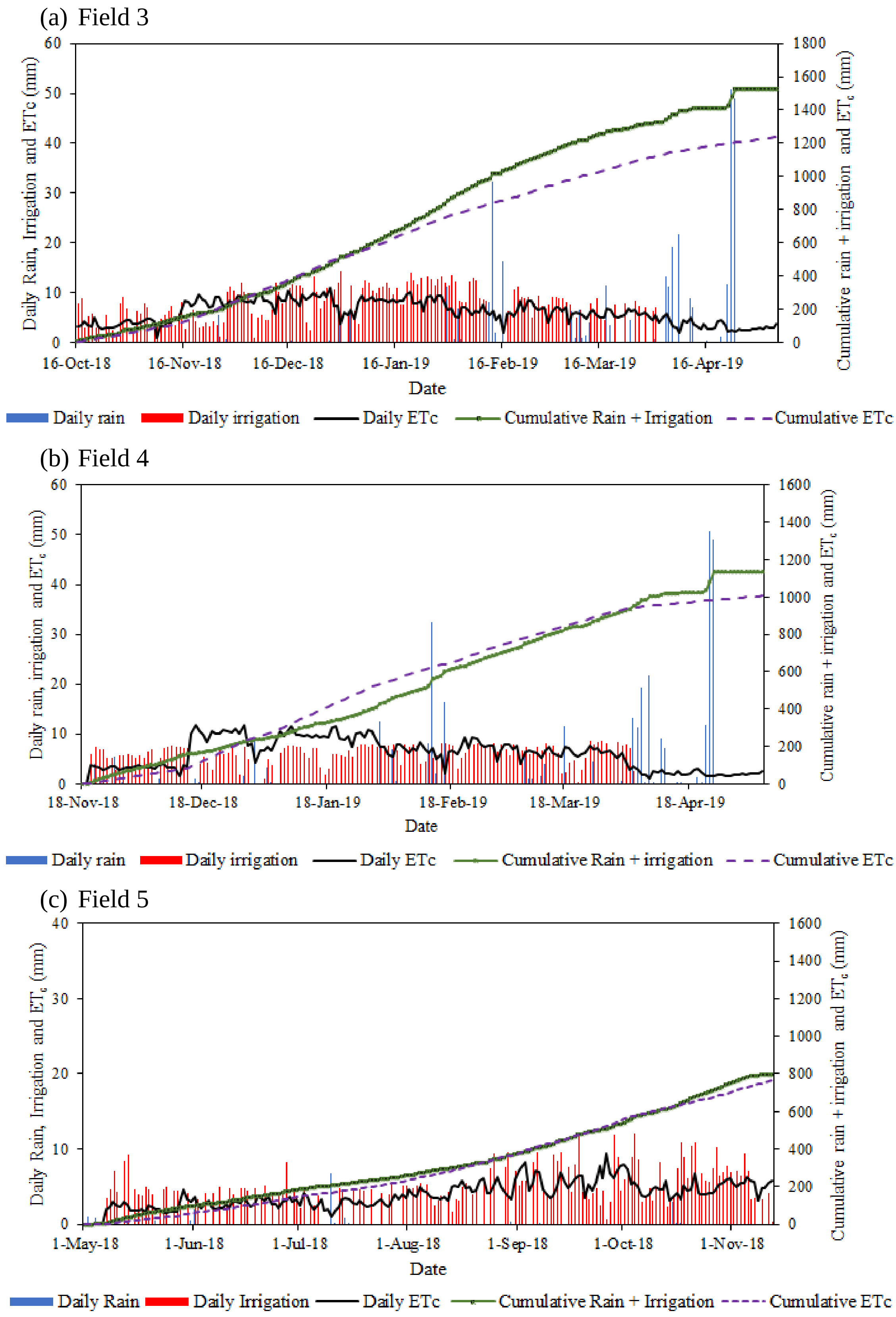


Figure 5-2: Daily rain, irrigation, crop evapotranspiration (ET_c), cumulative rain plus irrigation and cumulative ET_c for Field 3 (a), Field 4 (b) and Field 5 (c) applied to paprika, groundnuts and onion, respectively, from planting to harvest.

5.3.2.1.3 Irrigation water quality

Irrigation water was slightly alkaline with a pH of 8.2 (Table 5-5), but still within the normal pH range for irrigation water of 6.5 – 8.4 (Bauder et al. 2014). Electrical conductivity (EC) ranged from 0.69 – 0.86 mS cm^{-1}, posing low salinity hazard to the crops (Bauder et al. 2014). Irrigation water contained relatively high concentrations of nitrate (NO_3^-), calcium (Ca), magnesium (Mg) and sulphate (SO_4^{2-}) and provided a significant amount of nutrients to the subsequent crops. The irrigation water used for Field 3 had the highest concentration of Ca, Mg and SO_4 as compared to the irrigation water used for the other fields (Table 5-5). High Ca, Mg and SO_4^{2-} concentration was a clear indication of Ca- and Mg- carbonate salts in the irrigation water. Irrigation water used for all fields showed low Na levels relative to the sum of Ca and Mg concentration (low sodium adsorption ratio, SAR), which implied low sodicity effects that usually reduce water infiltration into the soil (Bauder et al. 2014).

Table 5-5: Irrigation water pH, electrical conductivity (EC), and mineral element concentration of ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), dihydrogen phosphate (H_2PO_4), potassium (K), calcium (Ca), magnesium (Mg), sulphate (SO_4), sodium (Na) and sodium adsorption ratio (SAR) for Field 3 (paprika), Field 4 (groundnuts) and Field 5 (onions).

Field	pH	EC (dS cm^{-1})	NH_4-N	NO_3-N	H_2PO_4	K	Ca	Mg	SO_4	Na	SAR
			mg L^{-1}								
3	8.2	0.86	0.3	15.6	0.8	9.0	81.8	48.1	30.8	22.5	0.5
4	8.2	0.69	0.2	19.2	1.2	9.0	48.2	27.1	18.4	39.0	1.1
5	8.2	0.72	0.7	4.8	0.7	9.0	57.7	24.4	19.7	49.7	1.4

5.3.2.2 Nutrient input sources

5.3.2.2.1 Initial soil nutrient content

Soil profile pH for Field 1 (4.3 – 4.8) and Field 4 (5.6 – 6.4) was slightly acidic, whereas, Field 3 and Field 5 soils had a neutral soil pH range of 6.2 – 7.1 (Table 5-4). Low CEC was observed for Field 1 and 3, which was due to very low clay content within the profile (Table 3-2). Fields 4 and 5 showed the highest average soil profile CEC of 7.1 and 6.4 $cmol_c$ kg^{-1}, respectively. This may be explained by the higher clay content of the profile for these two fields (Table 3-2).

Relatively high initial nutrient content was observed within the 0 – 0.9 m soil layer. Soil available P ranged from 129 – 181 kg ha^{-1} within the 0 – 0.3 m soil layer. Soil available P content showed a decreasing trend with soil depth. Soil exchangeable K^+ within the top 0 – 0.3 m soil layer ranging from 287 – 851 kg ha^{-1} was measured. Soil profiles for Fields 4 and 5 showed the highest soil exchangeable K^+ content that ranged between 495 – 651 kg ha^{-1}, and 192 – 851 kg ha^{-1}, respectively. This may be explained by the high clay content and CEC of the soil profile for these two fields (Table 5-6).

Soil exchangeable Ca^{2+} and Mg^{2+} observed within the top 0 – 0.3 m ranged between 975 – 3629 kg ha^{-1} Ca and 174 – 809 kg ha^{-1} Mg (Table 5-6). The very high Ca and Mg contents may be attributed to the presence of a chalky calcic hard pan layer in the soil profile for of the fields. For this reason, Ca and Mg contents were observed to increase with soil depth. Additionally, the growers usually apply high gypsum ($CaSO_4$) amounts (1-2 t ha^{-1}), which may have caused Ca accumulation in the soil profile over the years of continuous cultivation. Mineral S content observed within the 0 – 0.3 m soil layer ranged from 32 – 201 kg ha^{-1}. Initial soil nutrient results suggest that a substantial amount of nutrients was left in the soil after potato harvest.

Table 5-6: Soil pH, cation exchange capacity (CEC), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) content measured before planting of subsequent crops for Fields 1, 3, 4 and 5.

Field	Depth (m)	pH (H_2O)	CEC $cmol_c$ kg^{-1}	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	S (kg ha^{-1})
1	0-0.3	4.8	2.44	173.2	444.2	975.0	173.9	201.3
	0.3-0.6	4.3	2.25	38.2	465.7	831.6	126.3	224.4
	0.6-0.9	4.7	1.71	8.0	359.4	765.9	168.4	243.6
3	0-0.3	7.1	3.32	128.9	286.9	1861.9	408.6	32.1
	0.3-0.6	6.3	2.67	41.5	211,5	1705.5	309.5	15.7
	0.6-0.9	6.2	3.17	7.0	305.4	2073.4	448.9	20.7
4	0-0.3	5.6	5.93	146.7	635.6	2334.1	706.8	33.6
	0.3-0.6	5.6	7.46	88.0	494.7	2104.5	560.6	34.5
	0.6-0.9	6.4	8.03	48.0	650.5	4313.0	790.0	64.0
5	0-0.3	6.6	4.79	181.3	851.2	3628.6	809.2	55.0
	0.3-0.6	6.3	6.81	91.5	827.9	10144.2	1175.2	52.5
	0.6-0.9	6.7	7.67	29.4	191.5	1451.4	379.8	9.2

5.3.2.2.2 Nutrient inputs levels for the subsequent crops

Nutrient inputs from inorganic fertilizer sources, irrigation water and carried-over nutrients after the potato crop season are presented in Table 5-7. At Fields 3 and 5, the growers applied inorganic fertilizers to the paprika and onions, whereas Field 4 (groundnuts) did not receive inorganic fertilizers (Table 5-7). Estimated carried-over nutrients after potato harvest for Fields 3, 4 and 5 presented a significant source of nutrients to the subsequent crops, thus, low inorganic fertilizer amounts were applied (Table 5-7). Large amounts of Ca and Mg applied to the subsequent crops mainly came from irrigation water (Table 5-5).

Table 5-7: Nutrient input levels of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) from inorganic fertilizers, irrigation water and carried-over nutrients applied to paprika (Field 3), groundnuts (Field 4) and onions (Field 5) as subsequent crops grown after potato production in Louwna area.

Field	N	P	K	Ca	Mg	S
Inorganic fertilizer nutrients (kg ha^{-1})						
3	246	102	203	31	0	74
4	0	0	0	0	0	0
5	131	86	251	61	0	62
Irrigation water nutrients (kg ha^{-1})						
3	44	3	107	975	574	122
4	36	3	72	385	216	49
5	9	2	71	455	193	52
Carried-over nutrients after potato harvest (kg ha^{-1})*						
3	38	179	96	169	370	0
4	172	105	99	847	363	116
5	0	163	3	624	212	102
Total amount (kg ha^{-1})						
3	328	284	406	1175	944	196
4	208	108	171	1232	580	165
5	140	250	325	1141	405	216

*Nutrient balance at potato harvest minus nutrients leached during the fallow period. Negative nutrient balances indicated that zero nutrients were carried- over to the subsequent crop.

The highest nutrient input rates were observed for Field 3 (paprika), with total amounts of 328 kg ha^{-1} N, 284 kg ha^{-1} P, 406 kg ha^{-1} K, 1175 kg ha^{-1} Ca, 5944 kg ha^{-1} Mg and 196 kg ha^{-1} S (Table 5-7). Nutrients inputs of paprika observed in the present study can be compared to nutrient inputs of *Capsicum* sp. studied in previous research. Hari et al. (2007) obtained the highest paprika dry fruit yield when 150 kg ha^{-1} N, 60 kg ha^{-1} P and 90 kg ha^{-1} K was applied on red sandy loam soils with available N, P and K content of 158, 95 and 300 kg ha^{-1}, respectively. Application of N, P and K at a rate of 126 kg ha^{-1} N, 38 kg ha^{-1} P and 23 kg ha^{-1} K led to increased pepper fruit yield than the control plots (Aliyu et al. 2000). It was also observed that higher N, P and K application rates resulted in excessive vegetative growth and reduced fruit yield (Aliyu et al. 2000). The recommended N: P: K application rate for bell pepper (*Capsicum annuum* L.) in India has been reported to be 100: 22: 41 kg ha^{-1} (Appireddy et al. 2008). Gypsum application rate of 227 kg ha^{-1} in bell pepper was studied by Toivonen and Bowen (1999). Magnesium and S application rate of 24 and 32 kg ha^{-1}, respectively, have been used in bell pepper production (Toivonen and Bowen 1999).

The groundnuts received the least amounts of nutrients, since no inorganic fertilizer sources were applied to this field. According to Singh et al. (1997), a groundnut target grain yield of between 2 – 2.5 t ha^{-1} requires average nutrient application rates ranging from160 – 180 kg ha^{-1} N, 20 – 25 kg ha^{-1} P, 80 – 100 kg ha^{-1} K, 60 – 80 kg ha^{-1} Ca, 30 – 45 kg ha^{-1} Mg and 15 – 20 kg ha^{-1} S. In the present study, the nutrients carried- over after potato supplemented irrigation water nutrient supply to groundnuts, producing an acceptable grain yield of 3.4 t ha^{-1}. Adequate supply of macro-nutrients in groundnuts is important for pod filling and oil synthesis, which are key determinants of the final grain yield (Singh et al. 1997). However, soil and fixed N by groundnuts root nodules can provide enough N for optimum groundnut growth (Singh et al. 1997).

The onions received a total of 140 kg ha^{-1} N, 250 kg ha^{-1} P, 325 kg ha^{-1} K, 1141 kg ha^{-1} Ca, 405 kg ha^{-1} Mg and 216 kg ha^{-1} S (Table 5-7). Nasreen et al. (2007) found that combined application of cow manure at 5 t ha^{-1}, 39 kg ha^{-1} P, 75 kg ha^{-1} K together with 120 kg ha^{-1} N and 40 kg ha^{-1} S resulted in maximum onion plant growth and yield production. Onion requires adequate supply of nutrients for increased vegetative growth, bulb diameter, weight of bulbs, as well as bulb quality in terms of flavours and pungency (Nasreen et al. 2007, Rizk et al. 2012).

5.3.3 Yield components, harvest index and water use efficiency of subsequent crops

5.3.3.1 Paprika pepper

Paprika leaf, stem and fruit DM yield, HI, as well water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) are presented in Table 5-8. The paprika dry fruit yield of 5500 kg ha^{-1}, represented a HI of 74.5%. The aboveground parts (leaves and stems) DM was 1884.2 kg ha^{-1}. The WUE_{R+I} and IWUE were 3.59 and 4.62 kg dry fruit mm^{-1}, respectively (Table 5-8).

Table 5-8: Paprika pepper yield components (leaf DM, stem DM, dry fruit yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for Field 3.

Field	Crop	Leaf DM (kg ha^{-1})	Stem DM (kg ha $^{-1}$)	Dry fruit yield (kg ha^{-1})	HI (%)	WUE_{R+I} (kg mm^{-1})	IWUE (kg mm^{-1})
3	Paprika Pepper	808.6	1075.6	5500	74.5	3.59	4.62

Paprika dry fruit yield obtained for Field 3 was close to the range of 3350 – 5095 kg ha^{-1} reported for paprika grown under three water application regimes (456, 346 and 480 mm) during dry and hot summers of a Mediterranean climate type in Cordoba, Spain (Gonzalez-Dugo et al. 2007). The authors further observed that paprika stem plus leaf DM yields ranged between 6.5 – 9.0 t ha^{-1} and the recalculated IWUE for the three water application regimes of 456, 346 and 480 mm were 10.5, 9.7 and 10.6 kg dry fruit mm^{-1}, respectively (Gonzalez-Dugo et al. 2007). Marketable dry fruit yield between 3914 – 7626 kg ha^{-1} was obtained for three paprika pepper cultivars irrigated with 874 mm during a hot and dry summer season in Sanliurfa Province, Turkey (yield values recalculated from fresh fruit yield: assuming 20% DM content) (Kirnak et al. 2016). In the same study, the recalculated average WUE_{R+I} of paprika was 6.1 kg mm^{-1} (Kirnak et al. 2016). Shongwe et al. (2010) reported a dry fruit yield range of 2500 – 5100 kg ha^{-1} for paprika grown in a greenhouse in Luyengo, Swaziland. Therefore, a relatively good dry paprika fruit yield was obtained for Field 3

5.3.3.2 Groundnuts

Groundnut total DM, dry pod yield, dry grain yield, HI and WUE expressed as WUE_{R+I} and IWUE for Field 4 are presented in Table 5-9.

Table 5-9: Groundnut yield components (total dry matter, dry pod yield, dry grain yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for Field 4.

Field	Crop	Total dry matter yield[a] (kg ha^{-1})	Dry pod yield[b] (kg ha^{-1})	Dry grain yield (kg ha^{-1})	HI (%)	WUE_{R+I} (kg mm^{-1})	IWUE (kg mm^{-1})
4	Groundnuts	9201	4595	3400	36.9	3.00	4.25

[a] Total dry mass as a sum of leaves, stems and pods.
[b] The pods contained 74% of grains (husk factor of 26 %).

Similar results were also reported by Chibarabada et al. (2019), who obtained a total biomass range of 8020 – 10540 kg ha^{-1}, pod yield between 3360 – 4960 kg ha^{-1}, grain yield range of 1950 – 2900 kg ha^{-1} and HI range of 23.5 – 28.6% for groundnuts produced during the summer in KwaZulu-Natal, South Africa. The groundnut IWUE based on dry grain yield and crop ET ranged from 0.8 – 1.6 kg mm^{-1} for different irrigation schemes (Chibarabada et al. 2019). Grain yield of between 545 – 1155 kg ha^{-1} was obtained for rainfed groundnuts produced during the summer season in the Eastern Cape, South Africa (Mbonwa 2013). Mandal et al. (2019), reported pod yields between 1194 – 2056 kg ha^{-1} for groundnuts produced during the hot and dry summer season in Odisha, India. In their study, the crop WUE (calculated as ratio of pod yield to crop ET) ranged between 4.8 – 7.0 kg mm^{-1}, and IWUE range was 9.4 – 25.1 kg mm^{-1} (Mandal et al. 2019). Pod yields ranging from 1978 – 2433 kg ha^{-1} was obtained in groundnuts applied with total water inputs ranging from 180 – 418 mm, produced during summer seasons in eastern India (Bandyopadhyay et al. 2005). In the same study, WUE_{R+I} ranged from 5.8 – 11.0 kg mm^{-1} (Bandyopadhyay et al. 2005). Therefore, a relatively good groundnut yield and WUE was obtained for Field 4, considering that no inorganic fertilizers were added to the crop. This suggest that the nutrients carried-over after potato harvest supplemented irrigation water nutrients to promote groundnut growth and yield production (Table 5-7).

5.3.3.3 Onion

Onion yield components, HI and WUE parameters are presented in Table 5.10. Aboveground fresh and dry biomass yields were 21.8 and 2.4 t ha^{-1}, respectively. A fresh onion bulb yield of 42.5 t ha^{-1} was obtained for an irrigation strategy of 100% of the crop ET in Lower Rio Grande of Texas (Enciso et al. 2009). Dry onion yield ranging from 5.4 – 6.9 t ha^{-1} was obtained for onions produced under irrigation in Hungary (Ombodi et al. 2013). Fresh bulb yield ranging from 19.2 – 34.4 t ha^{-1} was reported by Kumar et al. (2007) for onion grown under different irrigation regimes in Punjab, India. However, fresh onion yield comparisons for different production regions is difficult since this variable is highly dependent on cultivar type, crop growth length, crop management practices, as well as curing period.

Onion IWUE of 95 kg fresh yield mm^{-1} for Field 5 compared well with the range of 69.74 – 90.22 kg fresh yield mm^{-1} reported by Kumar et al. (2007). Irrigation water use efficiency between 38 – 52 kg fresh yield mm^{-1} was obtained for fully irrigated onion with or without mulch produced during the dry season in northern Nigeria (Igbadun et al. 2012). The low IWUE was mainly due to very low bulb yields (13.1 – 20.6 t ha^{-1}) obtained under full irrigation treatments (Igbadun et al. 2012). Therefore, relatively high WUEs of the present study are explained by the relatively high fresh bulb yields obtained for Field 5 (Table 5-10).

Table 5-10: Onion yield components (aboveground biomass and bulb yield), harvest index (HI) and water use efficiency based on rain plus irrigation (WUE_{R+I}) and irrigation water use efficiency (IWUE) for both wet and dry samples.

Field 5	Fresh/Dry	Aboveground biomass (t ha^{-1})	Bulb yield (t ha^{-1})	Average* bulb mass (g)	Harvest index (%)	WUE_{R+I} (kg mm^{-1})	IWUE (Kg mm^{-1})
Onion	Fresh	21.8	75.0	116.8	77.5	93.11	95.00
	Dry	2.4	9.6	-	80.0	11.92	12.16

* Average bulb mass was taken from 20 bulbs (bulb weight ranged from 100 – 137 g).

5.3.4 Nutrient uptake and leaching

5.3.4.1 Plant nutrient uptake and nutrient harvest index

Nutrient uptake by the different plant parts for the subsequent crops for Fields 3, 4 and 5 is presented in Table 5-11. Nutrient harvest index represents the proportion of nutrients exported with harvestable economic product for each crop (Figure 5-3). The results revealed that paprika takes up large amounts of N and K, while P, Ca, Mg and S are taken up in relatively small quantities (Table 5-11). Paprika NHI results showed that about 80% of total N, P and K taken up by the crop is accumulated in harvestable fruits (Figure 5-3). Nitrogen, P and K uptake results for paprika were comparable to values reported by Hari et al. (2007), with uptake ranges of 48 – 137 kg ha^{-1} N, 18 – 39 kg ha^{-1} P and 92 – 208 kg ha^{-1} K. Determination of plant nutrient uptake is important to optimize nutrient management practices of crops (Thangasamy 2016).

Table 5-11: Nutrient uptake of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) for the different plant parts (leaves, stems and fruits/bulbs) of paprika (Field 3), groundnuts (Field 4) and onion (Field 5).

Field	Plant part	Nutrient uptake (kg ha^{-1})					
		N	P	K	Ca	Mg	S
3 (Paprika)	Leaves	20.1	2.3	15.1	35.4	19.6	3.3
	Stems	10.7	1.3	20.1	9.6	11.6	2.7
	Fruits	133.4	16.5	156.8	8.8	11.8	11.6
	Total	**164.2**	**20.1**	**192.0**	**53.7**	**43.0**	**17.6**
4 (Groundnuts)	Aboveground parts	72.0	5.1	77.2	78.7	35.7	9.2
	Pods	176.9	14.5	35.2	7.1	10.6	7.6
	Total	**248.9**	**19.6**	**112.3**	**85.8**	**46.3**	**16.8**
5 (Onion)	Aboveground parts	59.7	9.6	65.8	49.1	11.1	8.3
	Bulbs	153.4	47.6	187.5	60.1	18.8	32.4
	Total	**213.0**	**57.2**	**253.2**	**109.2**	**29.9**	**40.7**

For groundnuts N, K and Ca were taken up in relatively larger amounts as compared to P, Mg and S (Table 5-11). Singh (2004) documented that groundnuts with pod yield of 3.0 t ha^{-1} removed 192 kg ha^{-1} N, 22 kg ha^{-1} P, 60 kg ha^{-1} K, 77 kg ha^{-1} Ca, 25 kg ha^{-1} Mg and 15 kg ha^{-1} S. Of the total nutrients taken up by groundnuts, the pods accumulated 71 – 74 % N and P, 31% K, 8% Ca, 23% Mg and 45% S (Figure 5-3). Macro-nutrients of N, P and S are translocated from the leaves to pods during the pod filling stage, which results in high NHI of these nutrients (Singh 2004). Large proportions of total Ca and Mg taken up by the groundnut crop remained in the aboveground parts, so less Ca was exported out of the field with harvestable pods (Figure 5-3).

Onion nutrient uptake was similar to that observed in both paprika and groundnut crops (Table 5-11). Of the total nutrients taken up by the onion crop, 55 – 83% of all the macro-nutrients was accumulated in bulbs (Figure 5-3). Onion nutrient uptake of 78 kg ha^{-1} N, 13 kg ha^{-1} P, 65 kg ha^{-1} K, and 12 kg ha^{-1} S was reported by Thangasamy (2016). Nutrient uptake in onion bulbs as a percentage of dry mass ranged between 0.9 – 3.1% N, 0.4 – 0.8% P, 1.0 – 1.3% K, 0.2 – 0.3% Ca, 0.1 – 0.2% Mg and 0.1 – 0.3% S (Coolong et al. 2005).

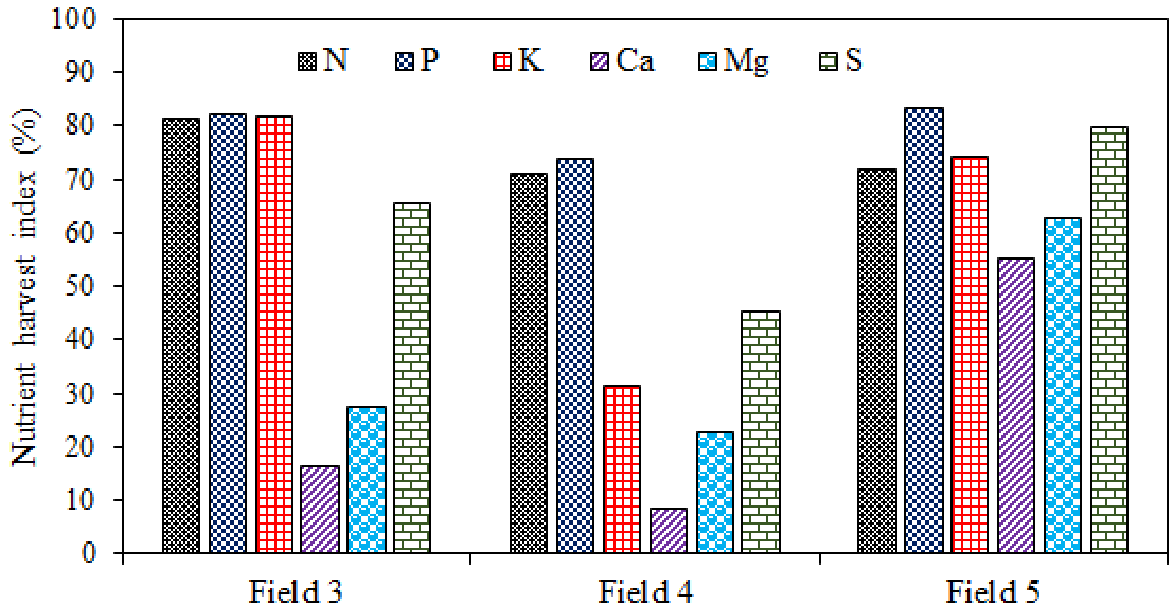


Figure 5-3: Nutrient harvest index in economic harvestable products for paprika fruits (Field 3), groundnuts grains (Field 4) and onion bulbs (Field 5).

5.3.4.2 Drainage and nutrient leaching

Field 1 was under fallow throughout the monitoring period (14 months) due to poor establishment of the follow-up crop (grass) (Table 5-1). Fallow periods for Fields 3 and 4 lasted 8 and 9 months, respectively, before planting the subsequent crops for the two fields (Table 5-1). Total drainage recorded during the fallow and subsequent crop growth periods for Fields 1, 3 and 4 were 409, 612 and 25 mm, respectively (Table 5-12). Field 5 was extensively monitored and therefore drainage was not measured. High drainage for Fields 1 and 3 may be explained by the large water inputs of 621 and 1530 mm, respectively, applied through rainfall and irrigation (Figure 5-1). In addition, Fields 1 and 3 have very sandy soils (91 – 94% sand) (Table 3-2), which were conducive to higher drainage and nutrient leaching (Table 5-10). It is important to note that there was no drainage in Field 3 during the potato crop mainly due to drainage restriction by the chalky calcic layer between 0.7 – 1.0 m depth. Therefore, it was difficult to explain the substantial drainage collected during the fallow and subsequent crop periods. However, this was probably due to water ponding on the calcic layer during the potato crop, and later there was slow drainage through the calcic layer, which could have occurred with increased water inputs from rain and irrigation during the fallow and subsequent crop periods.

Substantial drainage recorded during the fallow period may be explained by the high rainfall that was experienced between March and April 2018, when the evaporative demand was low (Table 5-4), therefore, excess rainwater within the soil profile was subject to drainage. Nutrient leaching during the fallow period substantially reduced the proportion of carried-over nutrients after potato harvest, most notable for Field 3 (Table 5-12). Paprika pepper in Field 3 was applied with large amounts of nutrients through inorganic fertilizers and irrigation water, which likely led to high nutrient leaching (Table 5-7). Conversely, Field 4 (planted with groundnuts) recorded the lowest drainage, as well as the lowest nutrient leaching. Field 4 received water inputs of 1134 mm, which was close to cumulative ET_o of 1079 mm, which likely reduced the risk of drainage and leaching (Figure 5-2b). Additionally, Field 4 had a soil profile with relatively high clay content (14 – 16%) and a limiting chalky layer, which probably slowed down free water drainage and nutrient leaching. Another possible explanation of low nutrient leaching for Field 4 may be due to the absence of inorganic fertilizer addition throughout the growing season (Table 5-7).

Table 5-12: Drainage amounts and leached nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) during the fallow period and subsequent crop growth periods for Fields 1, 3 and 4.

Field	Drainage (mm)	Nutrients leached (kg ha^{-1})					
		N	P	K	Ca	Mg	S
Fallow period							
1	409	2	1	22	40	9	14
3	226	20	1	17	770	102	392
4	22	0	0	2	52	10	5
Subsequent crop							
1	-	-	-	-	-	-	-
3	386	25	1	19	492	71	174
4	3	0	0	0	3	1	0
Total amounts							
1	409	2	1	22	40	9	14
3	612	45	2	36	1261	172	566
4	25	0	0	2	55	11	5

Calcium, Mg and S were the most leached nutrients during the fallow period and subsequent crop growth (Table 5-12). The same trend was observed in potato and was likely caused by the irrigation water containing relatively high Ca, Mg and S concentrations; hence, these nutrients were leached along with the drainage water (Table 5-5). High Ca and Mg concentrations in irrigation and drainage water could also have been due to the weathering of the chalky calcic layer observed within the soil profile for all fields, except Fields 1, 2 and 6.

5.3.5 Nutrient use efficiency of subsequent crops

5.3.5.1 Partial factor productivity

Partial factor productivity (PFP) of applied macro-nutrients for each subsequent crop (paprika, groundnuts and onion) is presented in Figure 5-4. The PFP quantifies the efficiency of applied nutrients in economic yield production (dry paprika fruit yield, dry groundnuts pods and fresh onion bulbs) (Dobermann 2007, Fixen et al. 2015). For Field 3 (paprika), S showed the highest PFP (28 kg dry fruit yield kg^{-1} applied S), whereas, Ca had the lowest PFP (4.7 kg dry fruit yield kg^{-1} applied Ca) (Figure 5-4a). For Field 4 (groundnuts), P had the highest PFP (32 kg dry grain yield kg^{-1} applied P) and Ca had the lowest PFP (6 kg dry grain yield kg^{-1} applied Ca) (Figure 5-4b). For Field 5 (onion), N had the highest PFP (535 kg fresh bulb yield kg^{-1} applied N) and Ca had the lowest PFP (66 kg fresh bulb yield kg^{-1} applied Ca) (Figure 5-4c). Generally, Ca and Mg had low PFP values for all the subsequent crops due to high input rates, specifically from irrigation water (Table 5-7).

Research on on-farm crop PFP of applied nutrients is scarce. Available on-farm studies carried out in developing countries, however, revealed that cereals PFP of N ranges between 44 – 49 kg grain yield kg^{-1} N (Dobermann 2007). It is important to note that a specific nutrient applied at the lowest rate will have the highest PFP, whereas, the nutrient applied in large quantities will show the lowest PFP (Dobermann 2007). However, a high PFP of a specific nutrient may not necessarily represent high use efficiency, since it is hard to quantify the naturally available soil nutrients taken up by the crop (Dobermann 2007).

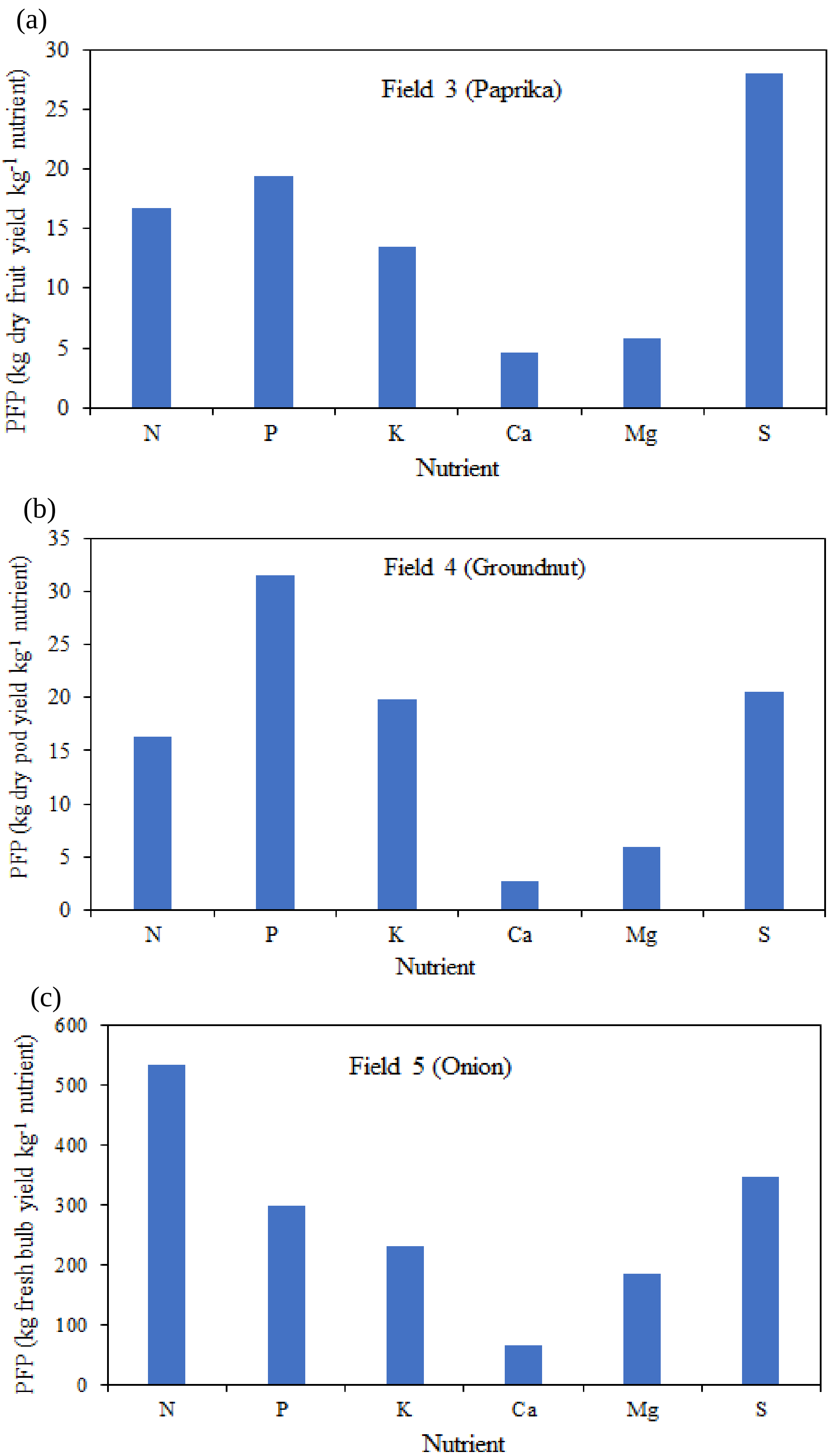


Figure 5-4: Paprika (a), groundnuts (b) and onion (c) partial factor productivity (PFP) of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S).

5.3.5.2 Overall nutrient balance of potato-based rotation systems

Nutrient balances help in assessing nutrient management practices of a cropping system and can be used as an indicator of the sustainability of production (Hanáčková et al. 2011, Venkatesh et al. 2017). Overall nutrient balance of a potato-based rotation system was estimated for intensively monitored Fields 3 and 4, where subsequent crops were planted after potato harvest (Field 3: potato – paprika, Field 4: potato – groundnuts). Results corresponding to the overall nutrient balances of N, P, K, Ca, Mg and S for Fields 3 and 4 are presented in Table 5-13. A positive nutrient balance of all nutrients was generally obtained in potato rotation systems for Fields 3 and 4. Field 3 (paprika) had a higher positive nutrient balance than Field 4 (groundnuts). This was mainly because Field 3 received relatively high inorganic fertilizer inputs as compared to Field 4, where no inorganic fertilizers were applied to the groundnuts (Table 5-7). Additionally, positive nutrient balances of all nutrients were probably due to incorporation of aboveground parts into the soil for both potato and the subsequent crops (aboveground plant parts were omitted in the nutrient balance calculation). These results show that a significant amount of nutrients can be left in the soil after a potato rotation system, especially when large amounts of inorganic fertilizer is applied to the subsequent crop.

The N, P and K balances of the present study can be compared to those observed in a rotation sequence of potato – onion – groundnuts, where a positive PNB for the three nutrients was obtained after potato and onion crops cycles when 180 kg ha^{-1} N, 35 kg ha^{-1} P and 100 kg ha^{-1} K were applied to the preceding potato crop (Trehan et al. 2008a). Average nutrient balance of -43 kg ha^{-1} N, 4 kg ha^{-1} P and -21 kg ha^{-1} K was obtained at the end of a potato – spring wheat rotation (Vos and Van der Putten 2004). Cropping systems involving potato; rice (*Oryza sativa* L.) – potato – rice, rice – potato – sesame (*Sesamum indicum* L.) and jute (*Corchorus olitorius* L.) – potato – rice, showed a positive nutrient balance of N and P (43 – 179 kg ha^{-1} N and 2 – 46 kg ha^{-1} P), whereas a negative K balance (42 – 203 kg ha^{-1} K) was obtained in West Bengal, India (values recalculated from nutrient inputs and plant nutrient removal) (Biswas 2017). A positive P balance of 3, 21 and 25 kg ha^{-1}, and a negative K balance of -130, -80 and -39 kg ha^{-1} were obtained after triple cropping systems of jute – potato – rice, rice – potato – rice and rice – potato – rice, respectively (Biswas et al. 2006). The positive nutrient balance observed for Fields 3 and 4 suggest that input rates of nutrients applied were relatively high, therefore the growers can be recommended to plant a third crop in rotation to utilize the residual nutrients, if there is enough water available.

Table 5-13: Nutrient inputs (A) (kg ha^{-1}), nutrient exports (B) (kg ha^{-1}) and overall nutrient balance of potato-based rotation system (C) (kg ha^{-1}) for Fields 3 and 4.

Nutrient	Field	Nutrient inputs (A)		Nutrient exports (B)*			Nutrient balance (C) = (A - B)
		Potato	Subsequent crop	Tubers	Fruit/Pods	Leaching	
		kg ha^{-1} per rotation cycle					
Nitrogen	3 (Paprika)	362.4	289.9	304.4	133.4	44.8	169.8
	4 (Groundnuts)	353.4	36.1	181.2	176.9	0.0	31.4
Phosphorus	3 (Paprika)	228.2	104.9	48.2	16.5	1.6	266.8
	4 (Groundnuts)	153.3	3.1	48.5	14.5	0.1	93.3
Potassium	3 (Paprika)	451.4	310.2	338.6	156.8	36.1	230.2
	4 (Groundnuts)	427.0	72.0	326.1	35.2	2.2	135.5
Calcium	3 (Paprika)	948.8	1005.9	10.2	8.8	1261.2	674.5
	4 (Groundnuts)	906.0	385.4	7.0	7.1	55.2	1222.1
Magnesium	3 (Paprika)	489.0	573.6	17.2	11.8	172.3	861.3
	4 (Groundnuts)	386.2	216.4	12.9	10.6	11.0	568.1
Sulphur	3 (Paprika)	158.0	196.2	24.7	11.6	565.8	-247.9
	4 (Groundnuts)	136.0	48.9	15.4	7.6	4.8	157.1

*Nutrient exports excluded nutrients taken up in crop residues of potato vines, paprika stems and leaves, and onion aboveground plant parts, since the growers leave crop residues in the field at crop harvest. Nutrient balance therefore represents a proportion of applied nutrients left after the two crop cycles, as well as nutrients accumulated in crop residues of both potato and the respective subsequent crop.

5.4 Conclusions

This study revealed that significant amounts of carry-over nutrients are left in the soil after potato harvest. The presence of nutrients carried-over after potato allowed for a reduction in the nutrient input rates to the subsequent crops of paprika, groundnuts and onions. Acceptable yields for the subsequent crops were obtained for Fields 3, 4 and 5, which suggest that nutrients carried-over after the potato crop supplemented the applied nutrients to promote plant growth and yield. However, substantial drainage during the fallow period led to nutrient leaching and a reduction of carried-over nutrients in the soil. Overall nutrient balance of the potato-based rotation systems for Fields 3 and 4 revealed that a large amount of nutrients applied were still left in the soil after the two crop cycles, when potatoes and subsequent crops are fertilized, and all crop residues are incorporated. It is therefore recommended that a third rotation crop be planted without nutrient addition for increased nutrient recovery and use efficiency.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Potato usually receives large amounts of water and nutrients. Moreover, the crop is inefficient in recovering applied water and nutrients, which leads to low water use efficiency (WUE) and nutrient use efficiency (NUE). Water use efficiency and NUE are important indicators of ecological sustainability in crop production.

Measurement of water and nutrient input rates and tuber yield of irrigated potato fields in the North West province provided useful information to explain WUE and NUE differences between growers within a region where production is done under relatively similar soil and weather conditions (Chapter 3). High potato yields (60 – 93 t ha^{-1}) were generally achieved, although substantial variability occurred between growers. Yield variability can be attributed to the differences in crop season length (114 – 132 days), soil conditions (texture and presence of chalky layer), crop management and amount and distribution of irrigation and rainfall during the season. Such factors affected the final tuber yield, WUE and NUE achieved for each field. Nevertheless, average measured tuber yield (83 t ha^{-1}) matched the average simulated potential yield (81 t ha^{-1}) for all fields well.

Total water inputs to potato crops were high (average of 962 mm) and greatly exceeded the average modelled irrigation requirements of 693 mm. Irrigation amounts (590 -1011 mm) applied to potato crops were not necessarily proportional to tuber yields. The potato field with the lowest total water input (590 mm irrigation and 19 mm rainfall) and acceptable yield (76 t ha^{-1}) had the highest WUE based on rain and irrigation (WUE_{R+I}) of 125 kg mm^{-1}. The lowest WUE_{R+I} was observed for the field that had the lowest yield (60 t ha^{-1}) and highest irrigation amount of 1011 mm.

Comparison between the average irrigation applied (866 mm) and average simulated irrigation requirements (693 mm) provided clear evidence of over-irrigation, which presented a risk of drainage and nutrient leaching from potato fields. Although some growers over-irrigated and some rain (average of 96 mm) was recorded in the growing season, drainage of 488 mm was only measured for one of the monitored potato fields, which was partly due to irrigation system malfunctioning. A chalky hard layer at about 0.8 – 1.0 m soil depth probably restricted drainage for some fields. Although no drainage was measured in the drainage lysimeters (DLs) in some fields, relatively high drainage amounts (121 – 389 mm) were expected for these fields. This suggests that drainage may still have occurred via sub-surface lateral flow that was not collected by the DLs. Moreover, the DL used in the present study has a low drainage collection efficiency at soil texture extremes, such as the very sandy soils of most monitored fields. The over-irrigation observed for some fields suggest that the growers probably do not use irrigation scheduling tools, therefore, adoption of irrigation scheduling practices is recommended to minimize water loss through drainage and increase WUE and NUE of irrigated potato.

Quantification of nutrient inputs, exports and leaching facilitated the estimation of NUE and partial nutrient balances of potato fields (Chapter 4). This also provided the required information for explaining NUE variability between potato growers. Macro-nutrients of nitrogen (N), phosphorus (P), potassium (P), calcium (Ca), magnesium (Mg) and sulphur (S) were applied through inorganic fertilizers and irrigation water. Large nutrient amounts were applied to potatoes and the quantities substantially varied between growers. Nutrient input rates from inorganic fertilizers were relatively similar for all fields, except for Field 6, which received considerably less of all the nutrients. Average inorganic fertilizer nutrient inputs were 276 kg ha^{-1} N, 217 kg ha^{-1} P, 309 kg ha^{-1} K, 136 kg ha^{-1} Ca, 17 kg ha^{-1} Mg and 47 kg ha^{-1} S. Irrigation water nutrients ranged from 2 – 84 kg ha^{-1} N, 2 – 3 kg ha^{-1} P, 53 – 91 kg ha^{-1} K, 222 – 774 kg ha^{-1} Ca, 109 – 465 kg ha^{-1} Mg and 12 – 124 kg ha^{-1} S. The substantial variations in total nutrient inputs observed between growers were mainly due to differences in the amounts of irrigation water applied and nutrient concentration thereof. This suggests that irrigation water quality should be considered when determining potato inorganic fertilizer rates to minimize the risk of excess nutrient application, which increases the risk of nutrient leaching.

Nutrient uptake results indicated that potato takes up N (414 kg ha^{-1}), K (591 kg ha^{-1}) and Ca (135 kg ha^{-1}) in large amounts, while P, Mg and S are taken up in relatively small amounts (less than 100 kg ha^{-1}). Therefore, the large Ca, Mg and S amounts applied, mainly through irrigation water, increased the risk of leaching of these nutrients, which resulted in low NUE. The recorded drainage (488 mm) for one of the potato fields resulted in nutrient leaching of 29 kg ha^{-1} N, 20 kg ha^{-1} K, 484 kg ha^{-1} Ca, 179 kg ha^{-1} Mg and 129 kg ha^{-1} S. Due to leaching, a negative partial nutrient balance for all nutrients was estimated for this field. This indicated that the excess nutrients exported through tuber harvest and leaching came from the soil. In the absence of nutrient leaching, a positive partial nutrient balance of all nutrients was estimated for most of the fields, which suggests that considerable amounts of applied nutrients are left in the soil and in crop residues after the potato harvest.

There was no consistent trend across the various NUE parameters of partial factor productivity (PFP), nutrient utilization efficiency (NUtE), and nutrient harvest index (NHI) for all fields. Partial factor productivity of all nutrients varied greatly between fields, which was due to substantial variations in total nutrient amounts applied to potato and the tuber yields achieved. Nutrient utilization efficiency and NHI showed small differences between fields, although total amounts of applied nutrients varied greatly between fields. This suggested that NUtE and NHI parameters were probably not affected by nutrient management practices of potato in the present study, therefore, they were not ideal indicators of NUE at field level. Hence, PFP can be considered as a good indicator of NUE in irrigated potato fields, since it was greatly affected by nutrient management and tuber yield variations. The PFP results for Field 6 revealed that NUE in potato production can be increased by achieving relatively high tuber yields with lower nutrient input rates, and thereby matching nutrient supply and demand very closely. Therefore, growers are recommended to adopt crop management practices that maximize tuber yield with reduced nutrient inputs. This can be achieved by adjusting inorganic fertilizer application rates based on initial soil and irrigation water nutrient status.

The effect of nutrients carried-over from potato on growth and NUE of the subsequent crop was evaluated for paprika, groundnuts and onion on three of the six monitored fields (Chapter 5). Subsequent crop yield was 5.5 t ha^{-1} dry paprika fruit, 3.4 t ha^{-1} dry groundnut pod yield and 75 t ha^{-1} fresh onion bulb yield. Nutrient amounts carried-over to the subsequent crops ranged from 38 – 172 kg ha^{-1} N, 105 – 179 kg ha^{-1} P, 3 – 99 kg ha^{-1} K, 169 – 847 kg ha^{-1} Ca, 212 – 363 kg ha^{-1} Mg and 102 – 116 kg ha^{-1} S. This allowed reduction in inorganic nutrients applied to paprika, groundnuts and onion, while still obtaining acceptable yields. Acceptable yield for the subsequent groundnut crop was achieved with no inorganic fertilizer application.

During the fallow period, drainage of 409, 226 and 22 mm was measured for three of the fields. Substantial drainage (386 mm) during the subsequent cropping season was only recorded from one of the monitored fields, which was irrigated with the highest amount (1192 mm). This drainage led to nutrient leaching (25 kg ha^{-1} N, 1 kg ha^{-1} P, 19 kg ha^{-1} K, 492 kg ha^{-1} Ca, 71 kg ha^{-1} Mg and 174 kg ha^{-1} S) from the subsequent paprika crop. These results indicate that significant drainage and nutrient leaching can occur during the fallow period when above average rainfall is received. Results for the overall nutrient balance of the potato-based rotation systems revealed that relatively large amounts of nutrients applied are left in the soil after the subsequent crop, when potato and the subsequent crops are fertilized, and all crop residues are incorporated. It is therefore recommended to plant a third crop in rotation with lower nutrient inputs for increased nutrient recovery and use efficiency.

In conclusion, incorporation of rotation crops after potato was identified as a practice to increase WUE and NUE of the overall cropping system. On-farm detailed measurement of WUE and NUE of potato-based rotation systems offer an opportunity to better understand water and nutrient management practices. Measuring WUE and NUE of the rotation systems, rather than those of potato alone, provided a true reflection of overall water use and nutrient recovery, as well as the potential environmental pollution risk associated with potato production.

6.1 Summary of key findings and recommendations for farmers

- Potato was over-irrigated for most of the fields, therefore it is recommended that irrigation scheduling tools be used to determine irrigation amounts.
- High irrigation amounts towards potato harvest can lead to tuber rot in soils with a limiting layer; hence, daily irrigation should be reduced towards the end of the growing season.
- Irrigation water can contain high concentrations of mineral nutrients, therefore it is recommended that the water used for irrigation be analysed to determine its nutrient status and the information be used when determining inorganic fertilizer application rates.
- Considerable amounts of nutrients are left in the soil after potato harvest, especially when the crop residues are incorporated into the soil.
- Large amounts of drainage and nutrient leaching were observed during the fallow period, which was mainly due to relatively high rainfall received. It is recommended to plant a winter crop if there is enough water available to minimize drainage and leaching.

6.2 Recommendations for future research

This study was carried out on a limited number of potato fields due to lack of enough measurement equipment, hence, further research is recommended, considering a larger number of fields to have a better understanding of the effect of nutrient management on WUE and NUE of potato-based rotation systems. Additionally, this study focused on in-field WUE and NUE measurements of potato-based rotation systems in a single production region of South Africa (SA). Therefore, further research is recommended to investigate WUE and NUE of potato production systems in different geographic locations of SA. It is recommended that a crop simulation model be employed to explore the effect of various combinations of irrigation level, nutrient input rate, soil type and weather conditions on WUE and NUE of potato production systems in SA at field level.

REFERENCES

Abbas H, Ranjan RS. 2015. Effect of soil moisture deficit on marketable yield and quality of potatoes. *Canadian Biosystems Engineering / Le Genie des biosystems au Canada* 57:1.25-1.37.

Aguilera J, Motavalli PP, Gonzales MA, Valdivia C. 2014. Response of a potato-based cropping system to conventional and alternative fertilizers in the Andean Highlands. *International Journal of Plant and Soil Science* 3:139–162.

Ahmadi SH, Plauborg F, Andersen MN, Sepaskhah AR, Jensen CR, Hansen S. 2011. Effects of irrigation strategies and soils on field grown potatoes: Root distribution. *Agricultural Water Management* 98:1280–1290.

Alfaro MA, Jarvis SC, Gregory PJ. 2004. Factors affecting potassium leaching in different soils. *Soil Use and Management* 20:182–189.

Aliyu L. 2000. Effect of organic and mineral fertilizers on growth, yield and composition of pepper (*Capsicum annuum* L .). *Biological Agriculture and Horticulture* 18:29–36.

Allen RG, Pereira LS, Raes D, Smith M. 1998. *Crop evapotranspiration (guidelines for computing crop water requirements)*. FAO irrigation and drainage paper No.56: FAO, Rome, Italy.

Allison MF, Fowler JH, Allen EJ. 2001. Responses of potato (*Solanum tuberosum* L.) to potassium fertilizers. *Journal of Agricultural Science* 136:407–426.

Alva AK. 2006. Sustainable nutrient management in sandy soils–fate and transport of nutrients from animal manure versus inorganic sources. *Journal of Sustainable Agriculture* 28:139–155.

Alva AK. 2010. Enhancing sustainable nutrient and irrigation management for potatoes. *Journal of Crop Improvement* 24:281–297.

Alva A, Fan M, Qing C, Rosen C, Ren H. 2011. Improving nutrient-use efficiency in chinese potato production: Experiences from the United States. *Journal of Crop Improvement* 25:46–85.

Ames M, Spooner DM. 2008. DNA from herbarium specimens settles a controversy about origins of the European potato 1. *American Journal of Botany* 95:252–257.

Amon-armah F, Yiridoe EK, Ahmad NHM, Hebb D, Jamieson R, Burton D, Madani A. 2013. Effect of nutrient management planning on crop yield, nitrate leaching and sediment loading in Thomas Brook Watershed. *Environmental Management* 52:1177–1191.

Appireddy GK, Saha S, Mina BL, Kundu S, Selvakumar G, Gupta HS. 2008. Effect of organic manures and integrated nutrient management on yield potential of bell pepper (*Capsicum annuum* L.) varieties and on soil properties. *Archives of Agronomy and Soil Science* 54:127–137.

Arauzo M, Valladolid M. 2013. Drainage and N-leaching in alluvial soils under agricultural land uses: Implications for the implementation of the EU Nitrates Directive. *Agriculture, Ecosystems and Environment* 179:94–107.

Badr MA, El-Tohamy WA, Zaghloul AM. 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. *Agricultural Water Management* 110:9–15.

Baligar VC, Fageria NK, He ZL. 2001. Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis* 32:921–950.

Baligar VC, Fageria NK. 2015. Nutrient use efficiency in plants: an oveview. In: Rakshit A, Sing HB, Sen A. (eds), *Nutrient use efficicency: From basics to advances*. New Delhi, India., Springer India. pp 1–13.

Bandyopadhyay PK, Rana SK, Mallick S. 2005. Water balance and crop coefficients of summer-grown peanut (*Arachis hypogaea* L.) in a humid tropical region of India. *Irrigation Science* 23:161–169.

Banerjee H, Rana L, Ray K, Sarkar S. 2016. Differential physiological response in potato (*Solanum tuberosum* L.) upon exposure to nutrient omissions. *Indian Journal of Plant Physiology* 21:129–136.

Bar-Tal A, Fine P, Yermiyahu U, Ben-Gal A, Hass A. 2015. Practices that simultaneously optimize water and nutrients use efficiency: Israeli experiences in fertigation and irrigation with treated wastewater. In: Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D (eds), *Managing water and fertilizer for sustainable agricultural intensification*. Paris, France, International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). pp 209–240.

Bauder TA, Waskom RM, Sutherland PL, Davis JG. 2014. Irrigation water quality criteria. Colorado State University Extension. Fact Sheet No. 0506. https://mountainscholar.org/bitstream/handle/10217/182905/AEXT_005062014.pdf?sequence=13

Begum M, Saikia M, Sarmah A, Ojah NJ, Deka P, Dutta PK, Ojah I. 2018. Water management for higher potato production: A Review. *International Journal of Current Microbiology and Applied Sciences* 7:24–33.

Belanger G, Walsh JR, Richards JE, Milburn PH, Ziadi NI. 2001. Tuber growth and biomass partitioning of two potato cultivars grown under different N fertilization rates with and without irrigation. *American Journal of Potato Research* 78:109–117.

Belanger G, Ziadi N, Walsh JR, Richards JE, Milburn PH. 2003. Residual soil nitrates after potato harvest. *Journal of Environment Quality* 32:607–612.

Beretta AN, Silbermann A V, Paladino L, Torres D, Bassahun D, Musselli R, García-lamohte A. 2014. Soil texture analyses using a hydrometer : Modification of the Bouyoucos method. *Ciencia e Investigacion Agraria* 41:263–271.

Beukema HP. Van der Zaag DE. 1990. Introduction to potato production. Wageningen, International Agriculture Centre- Pudoc iii, 208pp.

Birch PRJ, Bryan G, Fenton B, Gilroy EM, Hein I, Jones JT, Prashar A, Taylor MA, Torrance L, Toth IK. 2012. Crops that feed the world 8 : Potato : Are the trends of increased global production sustainable ? *Food Security* 4:477–508.

Biswas B. 2017. Cropping system analysis for agricultural sustainability - productivity, economy, ecology and energy use efficiency. *Journal of Experimental Biology and Agricultural Sciences* 5:294–301.

Biswas B, Ghosh DC, Dasgupta MK, Trivedi N, Timsina J. Dobermann A. 2006. Integrated assessment of cropping systems in the Eastern Indo-Gangetic plain. *Field Crops Research* 99:35–47.

Boem FHG, Rubio G, Barbero D. 2011. Soil phosphorus extracted by Bray 1 and Mehlich 3 soil tests as affected by the soil/solution ratio in Mollisols. *Communications in Soil Science and Plant Analysis* 42:220–230.

Cakmak I. 2008. Enrichment of cereal grains with zinc : Agronomic or genetic biofortification ? *Plant and Soil* 302:1–17.

Cambouris AN, Zebarth BJ, Nolin MC, Laverdière MR. 2008. Apparent fertilizer nitrogen recovery and residual soil nitrate under continuous potato cropping: Effect of N fertilization rate and timing. *Canadian Journal of Soil Science* 88:813–825.

Carli C, Condori B, Monneveux P, Mares V, Yuldashev F, Khalikov D. 2014. Effect of different irrigation regimes on yield, water use efficiency and quality of potato (*Solanum tuberosum* L.) in the lowlands of Tashkent, Uzbekistan: A field and modeling perspective. *Field Crops Research* 163:90–99.

Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM. 1996. Nitrogen-use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. *Field Crops Research* 47:1–12.

Chibarabada TP, Modi AT, Mabhaudhi T. 2019. Water use of selected grain legumes in response to varying irrigation regimes. *Water SA* 45:110–120.

Clough GH. 1994. Potato tuber yield, mineral concentration, and quality after calcium fertilization. *Journal of the American Society for Horticultural Science* 119:175–179.

Coolong TW, Kopsell DA, Kopsell DE, Randle WM. 2005. Nitrogen and sulfur influence nutrient usage and accumulation in onion. *Journal of Plant Nutrition* 27:1667–1686.

Darwish TM, Atallah TW, Hajhasan S, Haidar A. 2006. Nitrogen and water use efficiency of fertigated processing potato. *Agricultural Water Management* 85:95–104.

Davenport JR, Milborn PH, Rosen CJ, Thornton RE. 2005. Environmental impact of potato nutrient management. *American Journal of Potato Research* 82:321–328.

De Vries SC, Van de Ven GWJ, Van Ittersum MK, Giller KE. 2010. Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy* 34:588–601.

Dean B. 1994. *Managing the potato production system*. New York, Food Products Press, imprint of The Haworth Press, Inc., 181pp.

Decagon Devices 2018. Drain gauge G3: Operator's manual. 24.

Delgado JA, Ristau RJ, Dillon MA, Duke HR, Stuebe A, Follett RF, Shaffer MJ, Riggenbach RR, Sparks RT, Thompson A, Kawanabe LM, Kunugi A, Thompson K. 2001. Use of innovative tools to increase nitrogen use efficiency and protect environmental quality in crop rotations. *Communications in Soil Science and Plant Analysis* 32:1321–1354.

Departmet of Water Affairs and Forestry 1996. South African water quality guidelines (second edition). Volume 4: Agricultural water use: irrigation. Pretoria, CSIR Enviromental Services.

Dobermann A. 2007. Nutrient use ef fi ciency – measurement and management. In: International Fertilizer Industry Association (IFA) (ed), *Fertilizer best management practices: General principles, strategy for their adoption and voluntary initiatives vs regulations*. Paris, France, International Fertilizer Industry Association (IFA). pp 1–30.

Drechsel P, Heffer P, Magen H, Mikkelsen R, Singh H, Wichelns D. 2015. Managing water and nutrients to ensure global food security, while sustaining ecosystem services. In Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D. (Eds.). *Managing water and fertilizer for sustainable agricultural intensification.* International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). (1st edition), Paris, France.

Eissa MA. 2019. Efficiency of P fertigation for drip-irrigated potato grown on calcareous sandy soils. *Potato Research* 62:97–108.

Ekelöf J. 2014. Phosphorus application strategies in potato. Constraints and potential improvements. PhD Thesis, Swedish University of Agricultural Sciences, Sweden.

Enciso J, Jifon J, Wiedenfeld B. 2007. Subsurface drip irrigation of onions : Effects of drip tape emitter spacing on yield and quality. *Agricultural Water Management* 92:126–130.

Enciso J, Wiedenfeld B, Jifon J, Nelson S. 2009. Onion yield and quality response to two irrigation scheduling strategies. *Scientia Horticulturae* 120:301–305.

Errebhi M, Rosen CJ, Gupta SC, Birong DE. 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. *Agronomy Journal* 90:10–15.

Essington EM. 2015. Soil and water chemistry: An intergrative approach. (2^{nd} Edition). Boca Raton, Florida., CRC Press,Taylor & Francis, 633pp.

Fageria NK. 1998. Optimizing nutrient use efficiency in crop production. *Revista Brasileira de Engenharia Agrícola e Ambiental* 2:6–16.

Fageria NK. 2014. Nitrogen harvest index and its association with crop yields. *Journal of Plant Nutrition* 37:795–810.

Fageria NK, Baligar VC. 2005. Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy* 88:97–185.

Fageria NK, Baligar VC, Li YC. 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. *Journal of Plant Nutrition* 31:1121–1157.

FAOSTAT. 2017. World potato production quantity (tonnes), yields and harvested areas for 2016. Avaialable at http://www.fao.org/faostat/en/#data/QC. [Accessed 19 March 2018].

Feltran JC, Lemos LB, Vieites RL. 2004. Technological quality and utilization of potato tubers. *Scientia Agricola* 61:598–603.

Fernandes AM, Soratto RP. 2016. Phosphorus fertilizer rate for fresh market potato cultivars grown in tropical soil with low phosphorus availability. *American Journal of Potato Research* 93:404–414.

Fixen P, Brentrup F, Bruulsema T, Garcia F, Norton R, Zingore S. 2015. Nutrient / fertilizer use efficiency : measurement , current situation and trends. In Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D. (eds.), *Managing water and fertilizer for sustainable agricultural intensification*. International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). (1st edition), Paris, France. Pp 1–30.

Franke AC, Steyn JM, Ranger KS, Haverkort AJ. 2011. Developing environmental principles, criteria, indicators and norms for potato production in South Africa through field surveys and modelling. *Agricultural Systems* 104:297–306.

Franke AC, Haverkort AJ, Steyn JM. 2013. Climate change and potato production in contrasting South African agro-ecosystems 2 . Assessing risks and opportunities . *Potato Research* 56:51–66.

Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P. 2013. Sustainable intensification in agriculture : Premises and policies. *Science* 341:33–34.

Gee GW, Newman BD, Green SR, Meissner R, Rupp H, Zhang ZF, Keller JM, Waugh WJ, Van Der Velde M, Salazar J. 2009. Passive wick fluxmeters: Design considerations and field applications. *Water Resources Research* 45:1–18.

George MS, Lu G, Zhou W. 2002. Genotypic variation for potassium uptake and utilization efficiency in sweet potato (*Ipomoea batatas* L.). *Field Crops Research* 77:7–15.

George TS, Taylor MA, Dodd IC, White PJ. 2018. Climate change and consequences for potato production: A review of tolerance to emerging abiotic stress. *Potato Research* 60:239–268.

Gerendás J, Führs H. 2013. The significance of magnesium for crop quality. *Plant and Soil* 368:101–128.

Girma BT. 2017. Potato productivity, nutrient use efficiency and soil chemical property as influenced by organic and inorganic amendments in Arbegona District, Southern Ethiopia. Msc. Dissertation, Hawassa University, Ethiopia.

Gonzalez-Dugo V, Orgaz F, Fereres E. 2007. Responses of pepper to deficit irrigation for paprika production. *Scientia Horticulturae* 114:77–82.

Govindakrishnan P, Haverkort AJ. 2006. Ecophysiology and agronomic management. In: Gopal J, Khurana SMP. (eds), *Handbook of potato production, improvement, and postharvest management*. New York, Food Products Press, imprint of The Haworth Press, Inc. pp 179–229.

Guilpart N, Grassini P, Sadras VO, Timsina J, Cassman KG. 2017. Estimating yield gaps at the cropping system level. *Field Crops Research* 206:21–32.

Gunter CC, Palta JP. 2008. Exchangeable soil calcium may not reliably predict in-season calcium requirements for enhancing potato tuber calcium concentration. *American Journal of Potato Research* 85:324–331.

Hailu G, Nigussie D, Ali M, Derbew B. 2017. Nitrogen and phosphorus use efficiency in improved potato (*Solanum tuberosum* L.) cultivars in Southern Ethiopia. *American Journal of Potato Research* 94:617–631.

Hanáčková E, Macák M, Candráková E. 2011. The nutrients balance of crop rotation. *Research Journal of Agricultural Science* 43:62–68.

Hanley F, Jarvis RH, Ridgman WJ. 1965. The effects of fertilizers on the bulking of Majestic potatoes. *Journal of Agricultural Science* 65:159–170.

Hari GS, Rao P V, Reddy YN, Reddy MS. 2007. Effect of nitrogen and potassium levels on yield and nutrient uptake in paprika (*Capsicum annuum* L.) under irrigated conditions of Northern Telangana Zone of Andhra Pradesh. *Asian Journal of Horticulture* 2:193–196.

Haro RJ, Dardanelli JL, Otegui ME, Collino DJ. 2008. Seed yield determination of peanut crops under water deficit : Soil strength effects on pod set, the source – sink ratio and radiation use efficiency. *Field Crops Research* 109:24–33.

Haverkort AJ. 1990. Ecology of potato cropping systems in relation to latitude and altitude. *Agricultural Systems* 32:251–272.

Haverkort AJ, Kooman PL. 1997. The use of systems analysis and modelling of growth and development in potato ideotyping under conditions affecting yields. *Euphytica* 94:191–200.

Haverkort AJ, Bindraban PS, Conijn JG, Ruijter FJ. 2009. A crop production ecology (CPE) approach to sustainable production of biomass for food, feed and fuel. *Outlook on Agriculture* 38:249–258.

Haverkort AJ, Hillier JG. 2011. Cool Farm Tool-Potato: Model description and performance of four production systems. *Potato Research* 54:355–369.

Haverkort AJ, Sandaña P, Kalazich J. 2014. Yield gaps and ecological footprints of potato production systems in chile. *Potato Research* 57:13–31.

Haverkort AJ, Franke AC, Steyn JM, Pronk AA, Caldiz DO, Kooman PL. 2015. A robust potato model : LINTUL-POTATO-DSS. *Potato Research* 58:313–327.

Haverkort AJ, Struik PC. 2015. Yield levels of potato crops : Recent achievements and future prospects. *Field Crops Research* 182:76–85.

Hawkes J, Francisco-Ortega J. 1993. The early history of the potato in Europe. *Euphytica* 70:1–7.

Hay RKM. 1995. Harvest index : A review of its use in plant breeding and crop physiology. *Annals of Applied Biology* 126:197–216.

Hijmans RJ, Spooner DM. 2001. Geographic distribution of wild potato species. *American Journal of Botany* 88:2101–2112.

IFA (International Fertilizer Industry Association). 2009. The global“4R”nutrient stewardship framework. Paris, France: International Fertilizer Industry Association. IFA. IFADATA. Avalable at: http://ifadata.fertilizer.org/ucSearch.aspx. [Accessed 18 July 2018].

Hou X, Jones BT. 2000. Inductively coupled plasma optical emission spectrometry. In: Meyers RA. (eds), *Encyclopedia of analytical chemistry*. Chichester, John Wiley & Sons Ltd. pp 9468–9485.

Ierna A, Pandino G, Lombardo S, Mauromicale G. 2011. Tuber yield, water and fertilizer productivity in early potato as affected by a combination of irrigation and fertilization. *Agricultural Water Management* 101:35–41.

Igbadun HE, Ramalan AA, Oiganji E. 2012. Effects of regulated deficit irrigation and mulch on yield, water use and crop water productivity of onion in Samaru, Nigeria. *Agricultural Water Management* 109:162–169.

Jiang Y, Zebarth BJ, Somers GH, Macleod JA, Savard MM. 2012. Nitrate leaching from potato production in Eastern Canada. In: He Z, Larkin RP, Honeycutt CW. (eds), *Sustainable potato production: Global case studies*. New York, Springer Science+Business Media. pp 233–250.

Jones BJ. 2012. *Plant nutrition and soil fertility manual*. (2nd edn.) CRC Press. Boca Raton, Florida. Pp. 271

Jones C, Jacobsen J. 2009. Fertilizer placement and timing. Nutrient management module No. 11. Montana State University Extension Program. Avalaible at: https://certifiedcropadviser.org/files/certifications/certified/education/self-study/exam-pdfs/41.pdf. [Accessed 10 May 2018].

Karlsson H, Palta JP, Crump PM. 2006. Enhancing tuber calcium concentration may reduce incidence of blackspot bruise injury in potatoes. *HortScience* 41:1213–1221.

Kassam A, Friedrich T. 2012. An ecologically sustainable approach to agricultural production intensification : Global perspectives and developments. *Field Actions Science Reports* 1:1–7.

Kaur B, Kaur G, Asthir B. 2017. Biochemical aspects of nitrogen use efficiency: An overview. *Journal of Plant Nutrition* 40:506–523.

Khan SM, Jan N, Ulllah I, Younas M, Ullah H. 2007. Evaluation of various methods of fertilizer application in poatato (*Solanum tuberosum* L.). *Sarhad Journal of Agriculture* 23:889–894.

Kirnak H, Gokalp Z, Demir H, Kodal S, Yildirim E. 2016. Pepper yield and quality as affected by different irrigation levels. *Journal of Agricultural Science* 22:77–88.

Kleinhenz MD, Palta JP, Gunter CC, Kelling KA. 1999. Impact of source and timing of calcium and nitrogen applications on 'Atlantic' potato tuber calcium concentrations and internal quality. *Journal of American Society of Horticulture Science* 124:498–506.

Klikocka H, Kobiałka A, Juszczak D, Głowacka A. 2015. The influence of sulphur on phosphorus and potassium content in potato tubers (*Solanum tuberosum* L.). *Journal of Elementology* 20:621–629.

Kooman PK, Haverkort AJ. 1994. Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL-POTATO. *In*: Haverkort AJ, MacKerron DKL. (eds.), E*cology and modeling of potato crops under conditions limiting growth*. Kluwer Academic Publishers, Dordrecht. pp 41–60.

Kumar S, Imtiyaz M, Kumar A, Singh R. 2007. Response of onion (*Allium cepa* L.) to different levels of irrigation water. *Agricultural Water Management* 89:161–166.

Ladha JK, Pathak H, Krupnik TJ, Six J, Van Kessel C. 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy* 87:85–156.

Larkin R, Honeycutt C, Olanya O, Halloran J, He Z. 2012. Impacts of crop rotation and irrigation on soilborne diseases and soil microbial communities. In: He Z, Larkin RP, Honeycutt CW. (eds), *Sustainable potato production: Global case studies*. New York, Springer Science+Business Media. pp 23–42.

Lehmann J, Schroth G. 2003. Nutrient leaching. In: Schroth G, Sinclair FL. (eds) *Trees, crops and soil fertility*. New York, Oxford University Press. pp 152–166.

Li Y, Li J, Gao L, Tian Y. 2018. Irrigation has more influence than fertilization on leaching water quality and the potential environmental risk in excessively fertilized vegetable soils. *PLoS ONE* 13:1–23.

Liu F, Shahnazari A, Andersen MN, Jacobsen SE, Jensen CR. 2006. Physiological responses of potato (*Solanum tuberosum* L.) to partial root-zone drying: ABA signalling, leaf gas exchange, and water use efficiency. *Journal of Experimental Botany* 57:3727–3735.

Liu XJ, Wang JC, Lu SH, Zhang FS, Zeng XZ, Ai YW, Christie P. 2003. Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice-wheat cropping systems. *Field Crops Research* 83:297–311.

Love SL, Stark JC, Salaiz T. 2005. Response of four potato cultivars to rate and timing of nitrogen fertilizer. *American Journal of Potato Research* 82:21–30.

Machida-Hirano R. 2015. Diversity of potato genetic resources. *Breeding Science* 65:26–40.

Madramootoo C, Wiyo K, Enright P. 1992. Nutrient losses through tile drain from two potato fields. *Applied Engineering in Agriculture* 8:639–646.

Mandal KG, Thakur AK, Mohanty S. 2019. Paired-row planting and furrow irrigation increased light interception, pod yield and water use efficiency of groundnut in a hot sub-humid climate. *Agricultural Water Management* 213:968–977.

Mazurczyk W, Wierzbicka A, Trawczynski C. 2009. Harvest index of potato crop grown under different nitrogen and water supply. *Acta Scientiarum Polonorum* 8:15–21.

Mbonwa TN. 2013. Yield, protein and oil content of selected groundnut cultivars grown at two locations in the Eastern Cape, South Africa. Msc. Dissertation, University of KwaZulu-Natal.

Merdun H. 2012. Effects of different factors on water flow and solute transport investigated by time domain reflectometry in sandy clay loam field soil. *Water, Air, and Soil Pollution* 223:4905–4923.

Mikkelsen, Rob, Jensen, Tom L., Snyder, Cliff, Bruulsema, Tom W. 2012. Nutrient management planning and accountability. In Bruulsema TW, Fixen PE, Sulewski GD. (eds.), *4R Plant nutrition: A manual for improving the management of plant nutrition*. Norcross, GA, USA: International Plant Nutrition Institute.

Mikkelsen R, Hartz T, Mohammad M. 2015. Challenges of increasing water and nutrient efficiency in irrigated agriculture. In: Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D. (eds), *Managing water and fertilizer for sustainable agricultural intensification.* Paris, France, International Fertilizer Industry Association (IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute

(IPNI), and International Potash Institute (IPI). pp 168–186.

Millard P, Robinson D. 1990. Effect of the timing and rate of nitrogen fertilization on the growth and recovery of fertilizer nitrogen within the potato (*Solanum tuberosum* L.) crop. *Fertilizer Research* 21:133–140.

Miller JS, Rosen CJ. 2005. Interactive effects of fungicide programs and nitrogen management on potato yield and quality. *American Journal of Potato Research* 82:399–409.

Munoz F, Mylavarapu RS, Hutchinson CM. 2005. Environmentally responsible potato production systems: A review. *Journal of Plant Nutrition* 28:1287–1309.

Nasreen S, Haque MM, Hossain MA, Farid ATM. 2007. Nutrient uptake and yield of onion as influenced by nitrogen and sulphur fertilization. *Bangladesh Journal of Agriculture Research* 32:413–420.

Neumann A, Torstensson G, Aronsson H. 2012. Nitrogen and phosphorus leaching losses from potatoes with different harvest times and following crops. *Field Crops Research* 133:130–138.

Nieto CAO. 2016. Nitrogen use efficiency in potato: an integrated agronomic, physiological and genetic approach. PhD Thesis submitted to Wageningen University. ISBN: 978-94-6257-646-9

Nyiraneza J, Bizimungu B, Messiga AJ, Fuller KD, Fillmore SAE, Jiang Y. 2017. Potato yield and phosphorus use efficiency of two new potato cultivars in New Brunswick , Canada. *Canadian Journal of Plant Science* 97:784–795.

Ombodi A, Koczka N, Lugasi A, Daood HG, Berki M, Helyes L. 2013. Nutritive constituents of onion grown from sets as affected by water supply. *HortScience* 48:1543–1547.

Ozgen S, Palta JP, Kleinhenz MD. 2003. Influence of supplemental calcium fertilization on potato tuber size and tuber number. *Acta Horticulturae* 619:329–336.

Ozgen S, Karlsson BH, Palta JP. 2006. Response of potatoes (cv Russet Burbank) to supplemental calcium applications under field conditions : Tuber calcium, yield, and incidence of internal brown spot. *American Journal of Potato Research* 83:195–204.

Palta JP. 1996. Roles of calcium in plant responses to stresses: Linking basic resaerch to the solution of practical problems. *Horticulture Science* 31:150–157.

Panigrahi B, Panda SN, Raghuwanshi NS. 2001. Potato water use and yield under furrow irrigation. *Irrigation Science* 20:155–163.

Poberezny J, Wszelaczyñska E. 2011. Effect of bioelements (N, K, Mg) and long-term storage of potato tubers on quantitative and qualitative losses part II. content of dry matter and starch. *Journal of Elementology* 16:237–246.

Porter GA, Sisson JA. 1991. Response of russet burbank and shepody potatoes to nitrogen fertilizer in two cropping systems. *American Potato Journal* 68:425–443.

Potatoes South Africa. 2016. South African potato industry report final. www.potatoes.co.za/.../Potato%20SA%20Industry%20Report%20FINAL%20WEB%2. [Accessed 12 April 2018].

Prasad R, Hochmuth GJ, Boote KJ. 2015. Estimation of nitrogen pools in irrigated potato production on sandy soil using the Model SUBSTOR. *PLoS ONE* 10:1–20.

Rahman M, Shah N, Oad F. 2004. Evaluation of various methods of fertilizer application in potato (*Solanum tuberosum* L.). *Asian Journal of Plant Sciences* 3:260–261.

Rajita G, Mandal N. 2016. Review on transit time ultrasonic flowmeter. In: 2016 2nd International Conference on Control, Instrumentation, Energy and Communication, CIEC 2016. pp 88–92.

Reddy TY, Reddy VR, Anbumozhi V. 2003. Physiological responses of groundnut (*Arachis hypogea* L.) to drought stress and its amelioration : A critical review. *Plant Growth Regulation* 41:75–88.

Rens L, Zotarelli L, Alva A, Rowland D, Liu G, Morgan K. 2016. Fertilizer nitrogen uptake efficiencies for potato as influenced by application timing. *Nutrient Cycling in Agroecosystems* 104:175–185.

Rens LR, Zotarelli L, Rowland DL, Morgan KT. 2018. Optimizing nitrogen fertilizer rates and time of application for potatoes under seepage irrigation. *Field Crops Research* 215:49–58.

Ríos D, Ghislain M, Rodríguez F, Spooner DM. 2007. What is the origin of the European potato? Evidence from Canary Island landraces. *Crop Science* 47:1271–1280.

Rizk FA, Shaheen AM, Abd El-samad EH, Sawan OM. 2012. Effect of different nitrogen plus phosphorus and sulphur fertilizer levels on growth, yield and quality of onion (*Allium cepa* L.). *Journal of Applied Sciences Research* 8:3353–3361.

Roberts TL. 2008. Improving nutrient use efficiency. *Turkish Journal of Agriculture and Forestry* 32:177–182.

Roberts S, Vodraska R, Kauffman M. Gardener E. 1971. Methods of soil analysis used in the soil testing Laboratory at Oregon State University. Special Report No.321, Oregon State University Agricultural Experimenta Station.

Rosen CJ, Bierman PM. 2008. Potato yield and tuber set as affected by phosphorus fertilization. *American Journal of Potato Research* 85:110–120.

Rosen CJ, Kelling KA, Stark JC, Porter GA. 2014. Optimizing phosphorus fertilizer management in potato production. *American Journal of Potato Research* 91:145–160.

Rosen CJ. 2018. Potato fertilization on irrigated soils. University of Minnesota Nutrient Management Extension. Available at: https://extension.umn.edu/crop-specific-needs/potato-fertilization-irrigated-soils#potassium-1075464. [Accessed 27 January 2020].

Rural, Environment and Agricultural Development (READ). 2015. Climate Support Programme-vulnerability assessment North West Province. Available at: www.nwpg.gov.za/.../North%20West%20Climate%20Vulnerability%20Assessment.pd. [Accessed 15 April 2018].

Salam MA, Solaiman ARM, Karim AJMS, Saleque MA, Solaiman ARM, Karim AJMS. 2014. System productivity, nutrient use efficiency and apparent nutrient balance in rice-based cropping systems. *Archives of Agronomy and Soil Science* 60:747–764.

Sandaña P. 2016. Phosphorus uptake and utilization efficiency in response to potato genotype and phosphorus availability. *European Journal of Agronomy* 76:95–106.

SAS. 2008. *The SAS System for Windows*. SAS Inst. Inc., Cary, NC.

Senbayram M, Andreas G, Wahle V, Heike T. 2015. Role of magnesium fertilisers in agriculture: Plant–soil continuum. *Crop and Pasture Science* 66:1219–1229.

Sezen SM, Yazar A, Eker S. 2006. Effect of drip irrigation regimes on yield and quality of field grown bell pepper. *Agricultural Water Management* 81:115–131.

Shahnazari A, Liu F, Andersen MN, Jacobsen S-E, Jensen CR. 2007. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. *Field Crops Research* 100:117–124.

Shannon MC, Grieve CM. 1999. Tolerance of vegetable crops to salinity. *Scientia Horticulturae* 78:5–38.

Sharma UC. 1999. Loss of nitrogen through leaching and runoff from two potato land-use systems on different soils. In: *Impact of land-use change on nutrient loads from diffuse sources* (Proceedings of IUGG99 symposium HS3, Birmingham, July, 1999). Birmingham, IAHS. pp 27–32.

Sharma UC, Arora BR. 1987. Effect of nitrogen, phosphorus and potassium application on yield of potato tubers (*Solatium tuberosum* L.). *Journal of Agricultural Science* 108:321–329.

Sharma LK, Bali SK. 2017. A review of methods to improve nitrogen use efficiency in agriculture. *Sustainability* 10:1–23.

Sharma DK, Kushwah SS, Nema PK, Rathore SS. 2011. Effect of sulphur on yield and quality of potato (*Solarium tuberosum* L.). *International Journal of Agricultural Research* 6:143–148.

Shaviv A, Mikkelsen RL. 1993. Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation - A review. *Fertilizer Research* 35:1–12.

Shock CC, Pereira AB, Eldredge EC. 2007. Irrigation best management practices for potato. *American Journal of Potato Research* 84:29–37.

Shongwe VD, Magongo BN, Masarirambi MT, Manyatsi AM. 2010. Effects of irrigation moisture regimes on yield and quality of paprika (*Capsicum annuum* L.). *Physics and Chemistry of the Earth* 35:717–722.

Simonne AH, Simonne EH, Eitenmiller RR, Mills HA, Cresman CP. 1997. Could the Dumas method replace the Kjeldahl digestion for nitrogen and crude protein determinations in foods? *Journal of the Science of Food and Agriculture* 73:39–45.

Sims JT, Simard RR, Joern BC. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. *Journal of Environment Quality* 27:277–293.

Singh AL. 2004. Mineral nutrient requirement, their disorders and remedies in groundnut. In:. Basu MS, Singh NB (eds), *Groundnut research in India*. Junagadh, India pp, National Research center for groundnut (ICAR), 137–159.

Singh AL, Ghosh PK, Dayal D. 1997. Nutrient management in groundnut and groundnut based cropping systems. In: Ghonsikar CP, Shinde VS (eds), *Nutrient management practices in crops and cropping systems*. Junagadh, India, Scientific Publishers, India. pp 157–190.

Singh H, Sharma M, Goyal A, Bansal M. 2016. Effect of nitrogen and sulphur on growth and yield attributes of potato (*Solanum tuberosum* L.). *International Journal of Plant and Soil Science* 9:1–8.

Soil Classification Working Group.2018. *Soil classification: A natural and antthropogenic system for South Africa*. 3rd edn. ARC-Institute for Soil, Climate and Water, Pretoria.

Sparrow LA. 2012. Potato Nutrient Management in Tasmania, Australia. In: He Z, Larkin R Honeycutt W (eds), *Sustainable potato production: Global case studies.* New York, Springer Science+Business Media. pp 295–308.

Stark J, Westermann D, Hopkins B. 2004. Nutrient management cuidelines for Russet Burbank potatoes. University of Idaho Extension Buletin 840.

Steyn JM, Du Plessis HF, Fourie P, Hammes PS. 1998. Yield response of potato genotypes to different soil water regimes in contrasting seasons of a subtropical climate. *Potato Research* 41:239–254.

Steyn JM, Du Plessis HF. 2012. Fertilizer and nutrient defficiencies of potatoes. In: Denner FDN, Venter SL, Niederwieser JG (eds), *Guide to potato production in South Africa*. ARC-Roodeplat, Vegetable and Ornamental Plants Institute, Pretoria, South Africa.

Steyn JM, Franke AC, Van der Waals JE, Haverkort AJ. 2016. Resource use efficiencies as indicators of ecological sustainability in potato production : A South African case study. *Field Crops Research* 199:136–149.

Sun Y, Cui X, Liu F. 2015. Effect of irrigation regimes and phosphorus rates on water and phosphorus use efficiencies in potato. *Scientia Horticulturae* 190:64–69.

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.

Svubure O, Struik PC, Haverkort AJ, Steyn JM. 2017. Comparative analysis of irish potato (*Solanum tuberosum* L.) production in the farming sectors that emerged from Zimbabwe's radical land reform of 2000. *Potato Research* 60:1–22.

Swain EY, Rempelos L, Orr CH, Hall G, Chapman R, Almadni M, Stockdale EA, Kidd J, Leifert C, Cooper JM. 2014. Optimizing nitrogen use efficiency in wheat and potatoes : interactions between genotypes and agronomic practices. *Euphytica* 199:119–136.

Taiz L, Zeiger E. 2002. *Plant physiology*. Sinauer Associates, Inc., Sunderland, MA., 690pp.

Tekeste N, Dechassa N, Woldetsadik K, Dessalegne L, Takele A. 2018. Influence of nitrogen and phosphorus application on bulb yield and yield components of onion (*Allium Cepa* L.). *The Open Agriculture Journal* 12:194–206.

Tesfamariam EH, Annandale JG, Steyn JM, Stirzaker RJ. 2009. Exporting large volumes of municipal sewage sludge through turfgrass sod production. *Journal of Environment Quality* 38:1320–1328.

Thangasamy A. 2016. Quantification of dry-matter accumulation and nutrient uptake pattern of short day onion (*Allium cepa* L.). *Communications in Soil Science and Plant Analysis* 47:246–254.

Thomason W, Mando A, Bationo A, Balota M, Payne W. 2015. Crop productivity and water and nutrient use efficiency in humid and subhumid areas. In: Drechsel P, Heffer P, Magen H, Mikkelsen R, Wichelns D (eds), *Managing water and fertilizer for sustainable agricultural intensification.* Paris, France, International Fertilizer Industry Association

(IFA), International Water Management Institute (IWMI), International Plant Nutrition Institute (IPNI), and International Potash Institute (IPI). pp 109–139.

Thompson GD. 1991. The growth of sugarcane variety N14 at Pongola. *Mount Edgecombe Research Report* 7: 227 pp.

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. 2002. Agricultural sustainability and intensive production practices. *Nature* 418:671–677.

Toivonen PMA, Bowen PA. 1999. The effect of preharvest foliar sprays of calcium on quality and shelf life of two cultivars of sweet bell peppers (*Capsicum annuum* L.) grown in plasticulture. *Canadian Journal of Plant Science* 79:411–416.

Torstensson G, Aronsson H, Bergstrom L. 2006. Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden. *Agronomy Journal* 98:603–615.

Trehan S, Pandey S, Bansal S. 2009. Potassium nutrition of potato crop- the Indian scenario. Punjab, 2-9pp.

Trehan SP, Sharma RC, Roy SK. 2008a. Recycling of crop residues for efficient and optimum use of mineral fertilizers in potato-onion-groundnut rotation. *Advances in Horticultural Science* 22:191–196.

Trehan SP, Upadhayay NC, Sud KC, Kumar M, Jatav MK, Lal SS. 2008b. Nutrient management in potato. CPRI Technical Bulletin No. 90 Central Potato Research Institute, Shimla, Himachal Pradesh, India, 64 pp.

UN DESA (United Nations, Department of Economic and Social Affairs, Population Division). 2015. World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.

Van Ittersum MK, Rabbinge R. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52:197–208.

Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. 2013. Yield gap analysis with local to global relevance-A review. *Field Crops Research* 143:4–17.

Velu G, Ortiz-monasterio I, Cakmak I, Hao Y, Singh RP. 2014. Biofortification strategies to increase grain zinc and iron concentrations in wheat. *Journal of Cereal Science* 59:365–372.

Venkatesh MS, Hazra KK, Ghosh PK, Khuswah BL, Ganeshamurthy AN, Ali M, Singh J. Mathur RS. 2017. Long–term effect of crop rotation and nutrient management on soil–plant nutrient cycling and nutrient budgeting in Indo–Gangetic plains of India. *Archives of Agronomy and Soil Science* 63:2007–2022.

Vos J. 1997. The nitrogen response of potato (*Solanum tuberosum* L.) in the field : nitrogen uptake and yield , harvest index and nitrogen concentration . *Potato Research* 40:237–248.

Vos J. 2009. Nitrogen responses and nitrogen management in potato. *Potato Research* 52:305–317.

Vos J, MacKerron DKL. 2006. Basic concepts of the management of supply of nitrogen and water in potato production. In: Haverkort AJ, MacKerron DKL. (eds), *Management of nitrogen and water in potato production*. Wageningen, Wageninge Academic Publishers, pp15–33.

Vos J, Van der Putten PEL. 2000. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. I. Input and offtake of nitrogen, phosphorus and potassium. *Nutrient Cycling in Agroecosystems* 56:87–97.

Vos J, Van der Putten PEL. 2004. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. II. Effect of catch crops on nitrate leaching in autumn and winter. *Nutrient Cycling in Agroecosystems* 70:23–31.

Waddell JT, Gupta SC, Moncrief JF, Rosen CJ, Steele DD. 2000. Irrigation and nitrogen management impacts on nitrate leaching under potato. *Journal of Environmental Quality* 29: 251-261.

Wang X, Shen J, Liao H. 2010. Acquisition or utilization, which is more critical for enhancing phosphorus efficiency in modern crops? *Plant Science* 179:302–306.

Wani SP, Chander G, Uppal RK. 2015. Enhancing nutrrient use efficiencies in rainfed systems. In: Rakshit A, Sing HB, Sen A. (eds), *Nutrient use efficicency: From basics to advances*. New Delhi, India, Springer India, pp359–380.

Webb J, Sylvester-Bradley R, Seeney F. 2000. The fertilizer nitrogen requirement of cereals grown on sandy soils. *Journal of Agricultural Science* 80:263–274.

Westermann DT. 1993. Fertility management. In: Randall CR, Curwen D, Loria R, Gary AS (eds), *Potato health management*. Idaho, APS Press, pp 77–86.

Westermann DT. 2005. Nutritional requirements of potatoes. *American Journal of Potato Research* 82:301–307.

Westermann DT, James DW, Tindall TA, Hurst RL. 1994. Nitrogen and potassium fertilization of potatoes: Sugars and starch. *American Potato Journal* 71:433–453.

Westermann DT, Sojka RE. 1996. Tillage and nitrogen placement effects on nutrient uptake by potato. *Soil Science Society of American Journal* 60:1448–1453.

White PJ, Broadley MR. 2003. Calcium in plants. *Annals of Botany* 92:487–511.

White PJ, Broadley MR. 2009. Biofortification of crops with seven mineral elements often lacking in human diets –iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytologist* 182:49–84.

Woli P, Hoogenboom G. 2018. Simulating weather effects on potato yield, nitrate leaching, and profit margin in the US Pacific Northwest. *Agricultural Water Management* 201:177–187.

Yadav MR, Kumar R, Parihar CM, Yadav RK, Jat SL, Ram H, Meena RK, Singh M, Birbal A, Verma AP, Ghoshand A, Jat ML. 2017. Strategies for improving nitrogen use efficiency: A review. *Agricultural Reviews* 38:29–40.

Yuan BZ, Nishiyama S, Kang Y. 2003. Effects of different irrigation regimes on the growth and yield of drip-irrigated potato. *Agricultural Water Management* 63:153–167.

Zebarth B, Belanger G, Cambouris A, Ziadi N. 2012. Nitrogen fertilization strategies in relation to potato tuber yield , quality and crop N recovery. In: He Z, Larkin R, Honeycutt W (eds), *Sustainable potato production: Global case studies*. New York, Springer Science+Business Media, pp165–186.

Zebarth BJ, Leclerc Y, Moreau G. 2004a. Rate and timing of nitrogen fertilization of Russet Burbank potato: Nitrogen use efficiency. *Canadian Journal of Plant Science* 84:845–854.

Zebarth BJ, Tai G, Tarn R, De Jong H, Milburn PH. 2004b. Nitrogen use efficiency characteristics of commercial potato cultivars. *Canadian Journal of Plant Science* 7:589–598.

Zebarth BJ, Rosen CJ. 2007. Research perspective on nitrogen BMP development for potato. *American Journal of Potato Research* 84:3–18.

Zebarth BJ, Milburn PH. 2003. Spatial and temporal distribution of soil inorganic nitrogen concentration in potato hills. *Canadian Journal of Soil Science* 83:183–195.

Zhou Z, Plauborg F, Liu F, Kristensen K, Neumann M. 2018. Yield and crop growth of table potato a ffected by different split-N fertigation regimes in sandy soil. *European Journal of Agronomy* 92:41–50.

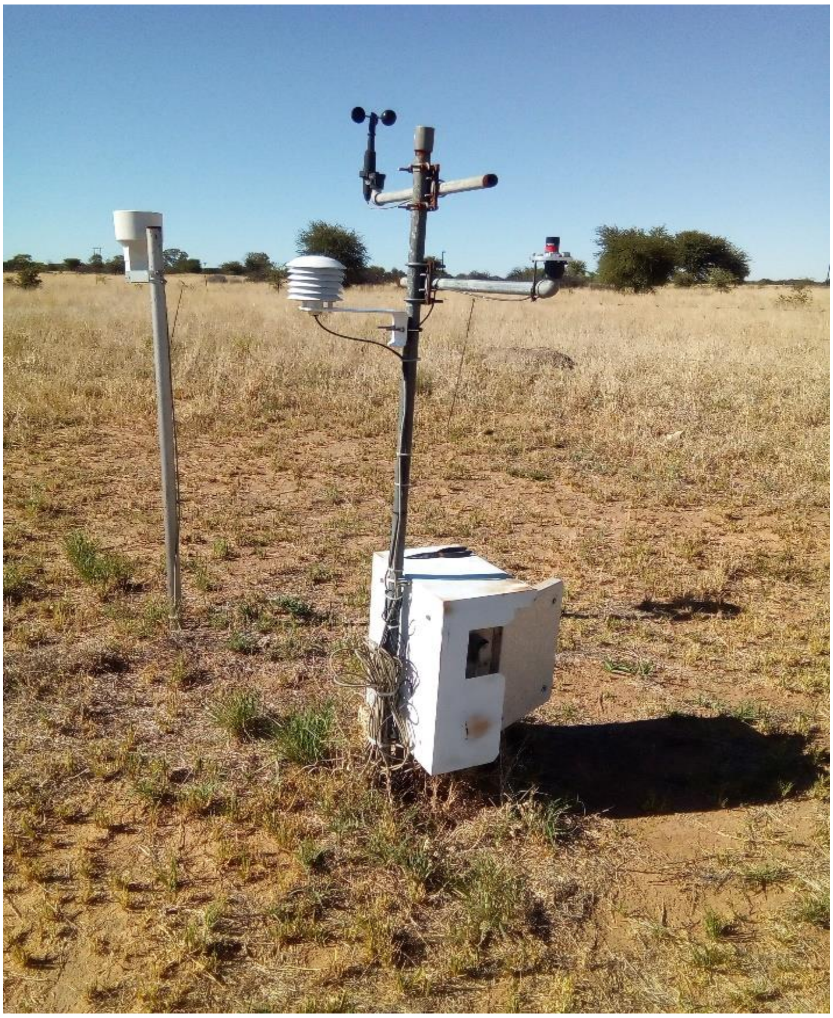
Zhu Y, Fox RH, Toth JD. 2002. Leachate collection efficiency of zero-tension pan and passive capillary fiberglass wick lysimeters. *Soil Science Society of America Journal* 66:37–43.

Zotarelli L, Rens LR, Cantliffe DJ, Stoffella PJ, Gergela D, Burhans D. 2015. Rate and timing of nitrogen fertilizer application on potato 'FL1867'. Part I: Plant nitrogen uptake and soil nitrogen availability. *Field Crops Research* 183:246–256.

Zotarelli L, Rens LR, Cantliffe DJ, Stoffella PJ, Gergela D, Fourman D, Fourman D. 2014. Nitrogen fertilizer rate and application timing for chipping potato cultivar atlantic. *Agronomy Journal* 106:2215–2226.

APPENDIX

Appendix 1: Automatic weather station (AWS) located at about 5 m away from Field 3.



Appendix 2: Decagon G3 drainage gauge lysimeter installation: divergence control tube (DCT) containing the collected intact soil core applied with diatomaceous earth on top (A), DCT connected to the lower section of the lysimeter (B), lysimeter lowered into 1 m pit at final installation point (C), access tube for drainage sensor and sample collection (D).

A

B

C

D

Appendix 3: Decagon G3 drainage lysimeter access pipe and EM500 data-logger in potato (Left) and subsequent groundnut (Right).

Appendix 4a: Location of calcic chalky layer observed within the 0.7 – 0.9 m of the soil profile for most of the fields.

Appendix 4b: Photograph of calcic hard layer concretions observed between the 0.7 – 0.9 m soil depth for some fields

Appendix 5: Pearson correlation coefficients between potato total input rates of nitrogen (N), phosphorous (P), potassium (K), Calcium (Ca), magnesium (Mg), sulphur (S) and tuber yield for all fields.

Pearson Correlation Coefficients, N = 6 Prob > |r| under H0: Rho=0							
	N	**P**	**K**	**Ca**	**Mg**	**S**	**Tuber yield**
N	1.0000	0.0419 0.9371	0.9213 0.0090	0.7884 0.0625	0.8037 0.0540	0.5894 0.2183	- 0.0798 0.8804
P	0.0419 0.9371	1.0000	0.3324 0.5198	-0.4157 0.4124	-0.3318 0.5206	-0.5323 0.2770	0.9684 0.0015
K	0.9214 0.0090	0.3324 0.5198	1.0000	0.6030 0.2051	0.58677 0.2209	0.3783 0.4596	0.2290 0.6625
Ca	0.7884 0.0625	-0.4156 0.4124	0.6030 0.2051	1.0000	0.9730 0.0011	0.9599 0.0024	- 0.4110 0.4182
Mg	0.8037 0.0540	-0.3318 0.5206	0.5868 0.2209	0.9730 0.0011	1.0000	0.9312 0.0069	- 0.3426 0.5062
S	0.5894 0.2183	-0.5322 0.2770	0.3783 0.4596	0.9599 0.0024	0.9312 0.0069	1.00000	- 0.4688 0.3484
Tube r yield	-0.0798 0.8804	0.9684 0.0015	0.2290 0.6625	-0.4110 0.4182	-0.3426 0.5062	-0.4688 0.3484	1.0000

Appendix 6: Centre-pivot irrigation system for potato production for all fields

Appendix 7: Subsequent crops of paprika pepper (1A and B), groundnut (2A and B) and onion (3A and B for Fields 3, 4 and 5, respectively.

1A

1B

2A

2B

3A

3B