COMPARISON OF HERITAGE AND MODERN CROP CULTIVARS IN RESPONSE TO IRRIGATION AND NITROGEN MANAGEMENT

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ISAAC RHINNEXIOUS FANDIKA

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ABSTRACT

There is a resurgence of interest in heritage crop cultivars (potatoes, squash and yams) in New Zealand because of the premiums farmers get at niche markets. However, a paucity of information in relation to their growth characteristics and resource use efficiency limit successful management of these crops. This research compares the response of different heritage and modern crop cultivars to irrigation, nitrogen (N) fertiliser and canopy management. Some heritage cultivars produced as much marketable yield as modern cultivars while other heritage cultivars had low yields. Modern potatoes were more responsive to irrigation and N than heritage potato crops (collectively known as Taewa). Application of more than 80 kg N ha^{-1} *decreased yield in Taewa (Moe Moe, Tutaekuri) whereas, it increased the yield of modern potatoes (Agria, Moonlight). Full irrigation (FI) increased yield in modern potatoes and Moe Moe. In contrast, Tutaekuri yield was greatest with partial irrigation (PI). FI and 80 kg N ha*$^{-1}$ *are recommended for Moe Moe production whereas PI and less than 80 kg N ha*$^{-1}$ *are recommended for Tutaekuri. In addition, greater tuber dry matter and low sugar content suggest that Taewa would have better cooking and processing qualities than modern potatoes. Heritage crops required more water than modern crop cultivars because they mature later. There was high 'water use efficiency' in heritage pumpkin squash; high 'irrigation water use efficiency' in modern potatoes and high 'economic water productivity' for heritage potatoes and pumpkin squash. Heritage crop cultivars adapted to water deficit by developing more roots, higher photosynthetic WUE and leaf water potential than modern cultivars. Although total biomass production was similar, heritage crops tended to produce less marketable yield than modern cultivars because of excessive vegetative growth and potato psyllid infestation. Two strategies to manage the canopy and reduce vegetative growth using chlorocholine chloride (CCC) and mechanical topping were developed. Both strategies increased marketable yield in Taewa by 32 - 44%. Application of CCC at 25 and 50 days after emergence (DAE) was recommended for irrigated Taewa, whereas mechanical topping and application of CCC at 25 and 30 DAE were recommended for both irrigated and rain-fed Taewa. The study also observed that potato psyllid need to be controlled up to 170 DAE in Taewa to avoid yield loss equivalent to NZ$10, 485 to NZ$17, 412 per ha. This study contributes to policy on sustainable and improved Maori land use. It can be concluded that premium market prices are important to the success of heritage crops (i.e. to maintain their high 'economic water productivity') whereas modern crops might use irrigation water more efficiently (i.e. greater 'water use efficiency'). It is evident that heritage crops can be grown successfully, and that on occasions they use valuable resources efficiently. To enhance water use efficiency, management of heritage crops should focus on improving the harvest index.*

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DEDICATION

This Thesis is dedicated to my late father (Limbikani Fandika) and late brothers (Moses Fandika & Misheck Njunga). I also dedicate this work to all people of Tchauya Primary School/Village (1979 - 1987), Chikapa Primary School (1987 - 1988), South Lunzu MCDE (1988 - 1990), Nyambadwe MCDE (1990 - 1992), Natural Resources College (1992 - 1994), Bunda College of Agriculture (1997 - 2002) and Cranfield University, Silsoe, UK (2003 - 2004) who assisted me on my voyage to fulfill this task.

What is the Meaning of Life in a Meaningless World, "Vanity of vanities? (Ecclesiastes 1:1-2). The meaning of life is in Christ Jesus "For we are His workmanship, created in Christ Jesus for good works, which God prepared beforehand, that we should walk in them." (Ephesians 2:10). But as many as received him, to them he gave power to become the sons of God, even to them that believe on his name (John 1:12).

CANDIDATE'S DECLARATION

This is to certify that the research carried out for my Doctoral Thesis entitled: "*Comparison of water use efficiency in heritage and modern crop cultivars in response to irrigation and nitrogen management*" in the Institute of Natural Resources, Massey University, Turitea Campus, New Zealand, is my own work, and that the thesis material has not been used in part or whole for any other qualification.

CANDIDATE'S NAME : ISAAC R FANDIKA

SIGNATURE :

DATE : 18/06/2012

SUPERVISOR'S DECLARATION

CHIEF SUPERVISOR'S NAME : PETER D. KEMP

SIGNATURE :

DATE : 13/6/2012

CO-SUPERVISOR'S NAME : James Millner

SIGNATURE : J P Miller

DATE : 13/6/12

CO-SUPERVISOR'S NAME : Dave Horne

SIGNATURE : DHorne

DATE : 13/6/2012

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GLOSSARY AND ABBREVIATIONS

ANOVA	Analysis of variance
A_n	Net photosynthesis
Ca	Calcium
CCC	Chlorocholine choline,
CWP	Crop water productivity
CWU	Crop water use or consumptive water use
^oC	Degree centigrade
CEC	Cation exchange capacity
Ci	Internal carbon concentration
DAE	Days after emergence
DAP	Days after planting
DII	Drought Intensity index
DM	Dry matter content
EWP	Economic water productivity
ET_c	Crop evapotranspiration
ET_o	Reference evapotranspiration
FI	Full irrigation
GLM	General Linear Model
GM	Geometric mean
g_s	Stomatal conductance
HI	Harvest index %
IWMI	International Water Management Institute
IWUE	Irrigation water use efficiency
Kg ha^{-1}	Kilogram per hactare
Kg ha^{-1} m^{-3}	Kilogram per hactare per cubic meter
K	Potassium
Kc	Crop coefficient
LAI	Leaf area index
LDMC	Leaf dry matter content
LSD	Least Significant Difference
LT	Leaf temperature
MAFF	Ministry of Agriculture, Forestry and Fisheries
MRZ	Maximum root zone

MAD	Maximum allowable deficit
m^3 ton^{-1}	Cubic meter per tonne
Mg	Magnesium
N	Nitrogen
Na	Sodium
NUE	Nitrogen use efficiency
NH_4^+-N	Ammonium-Nitrogen
NO_3^--N	Nitrate-Nitrogen
NPV	Net present value
PAR	Photosynthetically active radiation
PRD	Partial root-zone drying
PI	Partial irrigation
PR	Percentage reduction
PWUE	Photosynthetic water use efficiency
P_e	Rain-fed
P	Phosphorus
RCBD	Randomised complete block design
SAS	Statistical Analysis System software
SEM±	Standard error of mean
SG	Specific gravity
SLA	Specific leaf area
SPAC	Soil–Plant–Atmospheric Continuum
SMD_c	Critical soil moisture deficit
SWC	Soil water content
T	Transpiration rate
t ha^{-1}	Tonnage per hectare
TDR	Time-Domain Reflectometer
URI	Uniform variable irrigation
WF	Water footprint,
WUE	Water use efficiency,
VPD	Leaf vapour pressure deficit
VRI	Variable rate irrigation
VWC	Virtual water content

CHAPTER 1

GENERAL INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

Irrigation is very important to New Zealand in relation to drought or climate variability, and for ensuring that crops meet market specifications (MAF, 2002). New Zealand agriculture consumption of freshwater resources is 77%; this is just above the global average of 70% (Ministry for the Environment, 2006, New Zealand Government, 2000). The irrigated area has increased from 470, 000 to 750 000 ha . The dairy industry has the largest irrigated area, followed by cereals and vegetables (MAF, 2004a; New Zealand Statistics, 2009). Of the row crops, wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), peas *(Pisum sativum),* potato (*Solanum tuberosum*) ryegrass *(Lolium multiflorum)* and white clover seed (*Trifolium repens*) (MAF, 2004a) are predominantly grown with irrigation.

New Zealand is now considered to be one of the countries with high agricultural water use (Clothier *et al.,* 2010). Irrigated farm area and agricultural water consumption are increasing by 5% per annum. Agricultural water consumption is expected to double by 2013 (MAF, 2004b) because of anticipated issues around global food security, population increases, urbanization and climate change (SIWI *et al.,* 2005; Fowler, 1999; Kevin, 2001). As a consequence, surface and groundwater withdrawal and crop evapotranspiration, in addition to environmental pollution from fertilisers and pesticides, are accelerating (Francis *et al.,* 2003).

In general terms, freshwater is sufficient in New Zealand; however, the agriculture sector faces water scarcity at certain times due to high pumping cost (IWMI, 2000, 2002) and environmental degradation in its bid for crop diversification and intensification (Francis *et al.*, 2003). Water scarcity and environmental degradation are reducing the sustainability and profitability of irrigated crops (MAF, 2004b). In this situation, growers need to allocate water to crops which have a comparative advantage in water use and also premium national or global market prices (McLaughlin, 1985). Application of the concept of water use efficiency (WUE) can benefit farmers in resource use and profit optimization in New Zealand (Howell, 2001; Ford *et al.,* 2009).

1.2 Water use efficiency

The Ministry of Agriculture Forestry and Fisheries (MAFF) strategic plan for New Zealand agriculture considers improved WUE to be the key to sustainable development (Ford *et al.,* 2009; Martin *et al.,* 2006). Water use efficiency is one of the five physical indicators (energy, solid waste, WUE, greenhouse gas and ozone layer depletion) of a sustainable environment (Miskell, 2009). The significance of WUE primarily lies in sustainable water and nutrient use whilst preserving the quality of the aquatic environment. Water use efficiency is both a generic and specific term used for expressing sparing water use in agriculture, at plant level and in the field (Wise *et al.,* 2011; Howell, 2001).

In specific terms, WUE is defined as the quantity of crop yield (kg) per volume of water (m^3) used for production (Howell, 2001). In generic terms, WUE relates to maximising the returns from water resources, whilst minimising negative environmental effects (Wise *et al.,* 2011). Water use efficiency studies are essential in New Zealand agriculture to sustain the remarkable increases in irrigation and fertilizer use observed between 1960 to 2009 (MacLeod *et al.,* 2006; New Zealand Statistics, 2009). The focus of this thesis is on WUE of heritage species with novel value in a niche market in the cultural economy of New Zealand (Roskruge, 1999).

1.2.1 Importance of heritage crops in modern production systems

A heritage crop in this thesis is defined as a crop that Maori[1] people inherited from other parts of the world through importation during their migration or those adopted from early European settlers. These crops were traditionally produced in Maori agriculture (Roskruge, 1999). The heritage crops which migrated with Maori are: kumara (*Impomea batatus*); paper mulberry (*Broussonetia papyrifera*), taro (*Colocasia antiquorum*), gourd (*Lagenaria vulgaris*) and yam (*Dioscorea spp*). Taewa or Maori potato was adopted from European settlers though it is orally argued that Maori had some potato varieties in pre-European time (Roskruge, 1999). Taewa (*Solanum tuberosum* L., *Solanum andigena* Juz & Buk.) and heritage pumpkins, Kamokamo (*Curcubita pepo* Linn) have been used by Maori for over 200 years (Roskruge, 1999).

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[1] Maori are the indigenous Polynesian people of New Zealand.

The industry around potatoes, including potato breeding programs, has focused on producing more within a short period over slow producers like heritage crops. However, heritage crops contain many traits (e.g taste) that could be advantageous. Heritage crops are worthy of scientific investigation because most of them (e.g Taewa) have superior flavor, texture or colour and health benefits (Singh *et al.*, 2008; Lister, 2001); heritage crops increase biodiversity into agriculture; most heritage crops are self – selected, hence have potential to withstand biotic and abiotic stresses and easily regenerate from seed or tuber seed (Roskruge, 2010). A scientific investigation of heritage crops may also reinvigorate Maori agriculture where a focus is less.

It is claimed that heritage crop varieties endure partial water and nitrogen deficits (Siddique *et al.,* 1990a; Zebarth *et al.,* 2008). Therefore, heritage crops with high economic value have the potential to minimise the water footprint of agriculture, whilst optimising the economic benefits (McLaughlin, 1985). In other words, heritage crop cultivars in New Zealand offer the opportunity for low water use, high nutrition and 'novel' value. Meanwhile, premium prices are offered for Taewa and Kamokamo in New Zealand (Hayward, 2002; Lambert, 2008; McFarlane, 2007). Taewa attracts premium prices due to their novel table value as well as for their cultural value (McFarlane, 2007). Growers' interest in these heritage crops (ie Taewa) and other Southern America native crops have now increased, due to a niche domestic market and the cultural economy of New Zealand (Hayward, 2002; McFarlane, 2007). Consumer demand for yellow-flesh, purple skin, red flesh or multi-coloured native potato varieties from South America is also high in the USA (Voss *et al.*, 1999) and Europe, due to their natural flavour (Walker, 1996).

Modern potatoes (*Solanum tuberosum* L.) and modern pumpkins known as Buttercup squash (C*ucurbuta maxima* Duchesne) are typically produced on a large scale for conventional and export markets. Modern potato is classified as the New Zealand's highest exported processed fresh vegetable and it is generally used for domestic consumption, either as a table or processed potato. The level of exports of Buttercup squash has also increased above that of crown and heritage pumpkin known as Kamokamo cultivars. Buttercup squash is the fourth largest export horticultural crop, behind kiwifruit, apples and onions (Grant, 1989; Perry *et al.*, 1997).

Both modern and heritage crop cultivars have traits related to their yield, morphological and physiological characteristics that will affect the efficiencies with which they use water and nutrients (Abeledo *et al.*, 2011; Feil, 1992; Koc *et al.*, 2003 and Siddique *et al.,* 1990a, 2001). Appropriate water and soil management could possibly reduce the difference in potential yield between modern and heritage crop cultivars (Abeledo *et al.*, 2011). However, it is not known whether low yields in heritage cultivars in New Zealand are the result of inappropriate soil and water management, or if genetic traits severely limit yield potential. The majority of heritage crops, whether under rain-fed or irrigation, are produced without consideration of the physical, economic and environmental returns per amount of water used. The New Zealand irrigation sector attempts to reduce inefficiency by regulating application rates (Thomas *et al.,* 2006) through improved system design (Hedley *et al.,* 2009a) and irrigation training. In addition, growers need to be able to use water resources prudently by selecting suitable cultivars, in order to maximise yields and returns.

1.2.2 Importance of WUE concepts in crop production systems

Growers of standard and heritage crops in New Zealand are more concerned with the effectiveness of irrigation (i.e increased yield), rather than its efficiency (MAF, 2002, 2004a). Water use efficiency concepts are restricted by a lack of information on their relationship to agronomic performance. Water use indicators, such as WUE (Howell, 2001; Perry, 2007), economic water productivity (Molden *et al.*, 2001; Barker *et al.*, 2003), irrigation water use efficiency (Howell, 2001) and water footprint or virtual water content of crops (Hoekstra *et al.,* 2007) are likely to become very important in future. They are likely to impact on future market access, the prices grower receive and water conservation programs.

The physiological and morphological characteristics of heritage crops along with modern crops have not been sufficiently studied in New Zealand. The FAO office in the Asian and Pacific region has ranked research on heat or drought tolerance of potato cultivars, potato with high dry matter and low reducing sugar content (Pandey, 2008) along with efficient water management (Clothier *et al.*, 2010), as priority research areas. The objective of this research was to compare the growth patterns and WUE of different heritage and modern crop cultivars in response to irrigation, nitrogen and canopy management.

1.3 Research hypothesis and Specific objectives

The general research question posed was: ‘*What is the impact of irrigation and nitrogen on heritage crop cultivars, compared to modern crop cultivars, in relation to growth patterns, yield, environment and economic value per water used?*’ The specific objectives of this study were:

1. To compare water and nitrogen use efficiency in Taewa and modern potato cultivars subjected to different levels of irrigation and nitrogen, in the glasshouse.

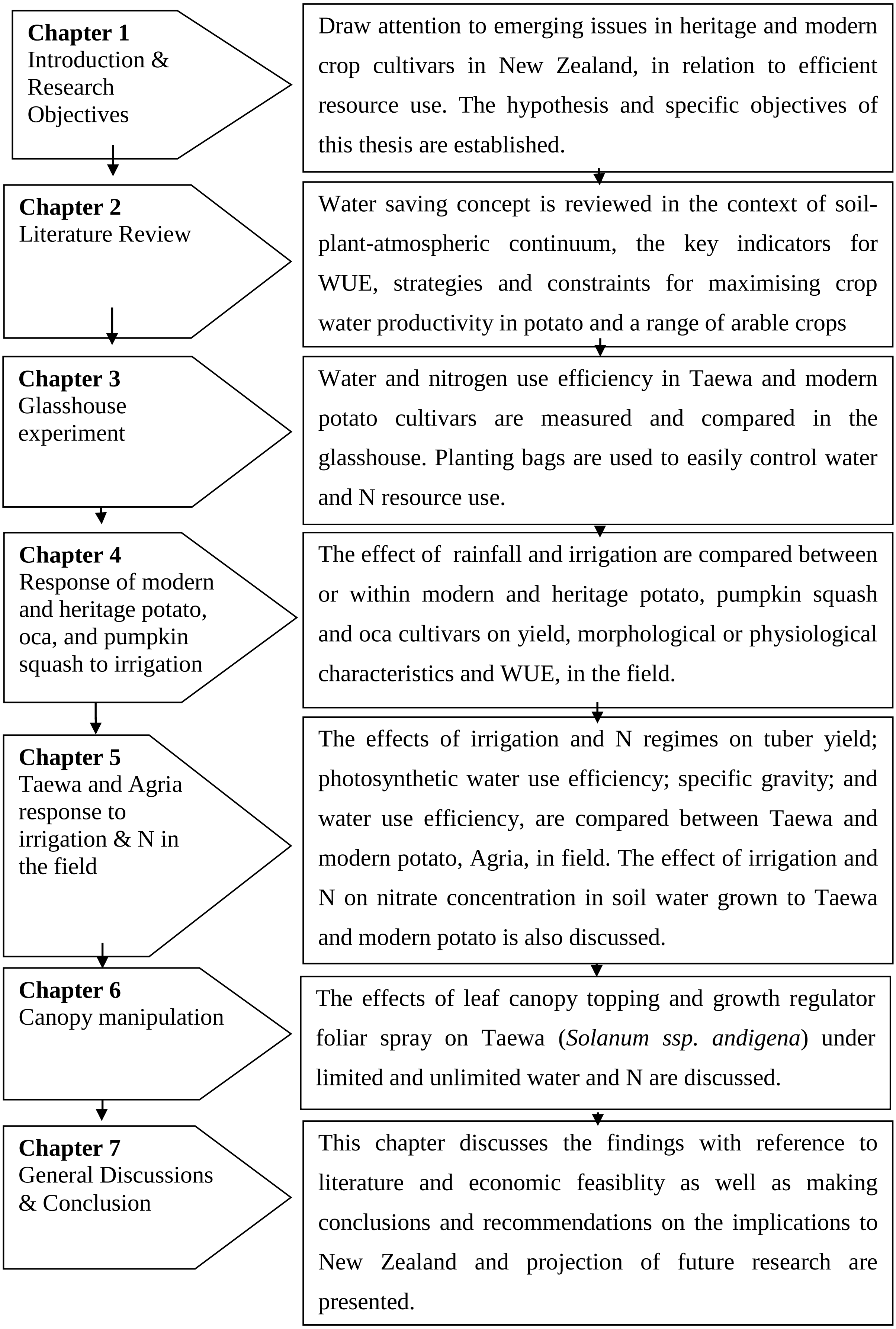
2. To compare key WUE indicators — irrigation water use efficiency, economic water productivity and water footprint — of heritage and modern potato, oca and pumpkin squash cultivars, under different soil moisture regimes, in the field.

3. To investigate the effect of irrigation and nitrogen management on Taewa yields, in addition to physiological characteristics, total sugars, tuber dry matter content, residual nitrogen leaching patterns, specific gravity and water use efficiency, compared to modern potato cultivars, in the field.

4. To improve the yield and WUE of a Taewa cultivar, Tutaekuri (*Solanum ssp. andigena*), using hormonal and mechanical leaf canopy manipulation, under limited and unlimited water and nitrogen environment, in the field.

5. To compare the economic feasibility of growing Taewa and modern potato cultivars using small scale irrigation.

1.4 Thesis outline



Chapter 1
Introduction & Research Objectives

Draw attention to emerging issues in heritage and modern crop cultivars in New Zealand, in relation to efficient resource use. The hypothesis and specific objectives of this thesis are established.

Chapter 2
Literature Review

Water saving concept is reviewed in the context of soil-plant-atmospheric continuum, the key indicators for WUE, strategies and constraints for maximising crop water productivity in potato and a range of arable crops

Chapter 3
Glasshouse experiment

Water and nitrogen use efficiency in Taewa and modern potato cultivars are measured and compared in the glasshouse. Planting bags are used to easily control water and N resource use.

Chapter 4
Response of modern and heritage potato, oca, and pumpkin squash to irrigation

The effect of rainfall and irrigation are compared between or within modern and heritage potato, pumpkin squash and oca cultivars on yield, morphological or physiological characteristics and WUE, in the field.

Chapter 5
Taewa and Agria response to irrigation & N in the field

The effects of irrigation and N regimes on tuber yield; photosynthetic water use efficiency; specific gravity; and water use efficiency, are compared between Taewa and modern potato, Agria, in field. The effect of irrigation and N on nitrate concentration in soil water grown to Taewa and modern potato is also discussed.

Chapter 6
Canopy manipulation

The effects of leaf canopy topping and growth regulator foliar spray on Taewa (*Solanum ssp. andigena*) under limited and unlimited water and N are discussed.

Chapter 7
General Discussions & Conclusion

This chapter discusses the findings with reference to literature and economic feasiblity as well as making conclusions and recommendations on the implications to New Zealand and projection of future research are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The scope of this review is in four thematic areas: (i) potential WUE indicators — key definitions and typical WUE, for a range of arable crops under rain-fed and irrigation; (ii) Soil–Plant–Atmospheric Continuum (SPAC) and physiological mechanisms of WUE in crops; (iii) Taewa species and production trends in New Zealand and (iv) strategies and constraints for maximising agronomic WUE in arable crops. Since a general summary of a WUE topic would be exceedingly broad to attempt here, the review focuses on potato (*Solanum tuberosum*), whilst oca (*Oxalis tuberosa*) and pumpkin squash (C*ucurbita spp.*) are included within Chapter 4. Considering that the benefits of irrigation are dependent on climate and the nature of the production system, this research is specific for New Zealand. However, the researcher has examined the literature on other regions in the world, in order to understand and obtain a 'picture' as to how potato performs in other climate zones, as a result of the limited information available within the WUE field in New Zealand.

2.2 Water use efficiency concept and indicators: key definitions

2.2.1 Rationale for WUE concepts

Smith (2000) concluded that agricultural water-saving strategies (water saving crops, fertilisation and deficit irrigation), which have demonstrated a great potential to improve water conservation, need to be embraced. Key indicators within such a framework of WUE are : crop water productivity and yield response factors, k_y (Kassam *et al.*, 2001); economic water productivity (Molden et al., 2001); water footprint or virtual water content (Hoekstra *et al.*, 2007); and irrigation water use efficiency concepts (Howell, 2001). These indicators are widely assessed as being the tools for attaining water security and efficient water use, in addition to connecting water consumption patterns and their impact on water resources and the environment (Hoekstra, 2003; English *et al.*, 1996). Hedley *et al.* (2009b) also refer to irrigation water use efficiency (IWUE), cost of saving, energy used, virtual water content and nitrate leaching as key generic WUE indicators in assessing irrigation performance in New Zealand.

Agricultural water saving tools are an essential means of appraising how crops convert water to biomass. These tools also guide on how water can be efficiently and effectively used, by utilising different technologies, at various locations and periods, during agriculture operations (Renault, 2002; Zimmer *et al.*, 2003). Henceforth, WUE indicators can help to identify crops with a comparative advantage (at different locations), thereby contributing to global water use efficiency. However, there are conflicting views on WUE concepts. Some scientists argue that the concept of WUE does not show the *actual* economic value of the water saving or loss (Zoebl, 2006) — and sometimes the results are contradictory (Zwart *et al.,* 2004) — whilst the water footprint calculation has been accused of being based only on hypothetical crop and water usage (Maes, 2009).

2.2.2 Crop water productivity and crop-water production function

2.2.2.1 Crop water productivity (kgha mm^{-1})

Water use efficiency as a specific term, as per Howell's (2001) review, is also refered to as crop water productivity (CWP) (Kassam *et al.*, 2001; Zwart and Bastiaanssen, 2004). Crop water productivity provides a measure of appraising agronomic mechanisms (variety selection, irrigation and fertilisation strategies), as efficient options for agricultural water management. Farmers and agronomist also define CWP as the ability of a crop to transform available water (through rainfall, irrigation and the contribution of soil water storage) into economic crop biomass yields (kgha^{-1} m^{3} or kgha^{-1} mm) (Howell, 2001; Perry, 2007). Water use efficiency as a specific term can also be defined in terms of crop photosynthetic capacity, per unit of plant transpiration, thus photosynthetic water use efficiency (photosynthetic WUE) (Xu & Hsiao, 2004). Kijne *et al.* (2003) indicated that CWP improves, through more crops being produced per amount of water, or by raising crop yields per unit of water consumed. Scientists have also pointed out that CWP, based on biomass yield, is more constant than photosynthetic WUE, because the later varies with CO_2 levels and environmental factors (Xu & Hsiao, 2004).

The attainment of water-saving, through the enhancement of output per water input, is achieved with a restricted water supply (Sander *et al.,* 2004), whilst the latter is achieved by optimising harvest index per water consumed (Siddique *et al.*, 2001).

2.2.2.1.1 Typical crop water productivity for a range of crop categories

Typical CWP, for a range of crop categories, varies with crop or cultivar, management system, year or location and part of the harvested crop (Nielsen, *et al.*, 2005, 2006). Crop water productivity, based on total yield biomass, was reported as being the highest in crops with low evaporative demand: and lowest in grain crops in the USA, according to Nielsen *et al.* (2006). Forage crops had the highest CWP of 14.5 kgDMha^{-1}mm^{-1}, with a decline to 4.2 kgDMha^{-1}mm^{-1} in oilseeds and 2.8 kgDMha^{-1}mm^{-1}, respectively, in small grain legumes, whether grown in rotation or continuously (Nielsen *et al.,* 2005).

In another similar study conducted in Australia, CWP for forage maize crops was between 38 and 58 KgDMha^{-1}mm^{-1} for irrigation water use and 28 KgDMha^{-1}mm^{-1} and 34 KgDMha^{-1}mm^{-1} for total water use, which was higher than for other forage crops (Greenwood *et al.*, 2004). It was also found that CWP amongst forage crops was affected by climate, where cool season grasses had lower CWP, compared to tropical grasses. The CWP of tropical grasses ranged between 21 to 43 kg ha mm^{-1} and 12 - 13 kgDMha^{-1} mm^{-1} under rain-fed and irrigated conditions, respectively. The CWP of cool season grasses ranged between 13 - 16 and 19 - 35 kgDMha^{-1}mm^{-1} under rain-fed and irrigated conditions, respectively (Callow *et al.*, 2004). Nitrogen was also reported to have increased CWP, from 6 and 13.9 kgDMha^{-1}mm^{-1} to 22.6 kgDMha^{-1} mm^{-1} with 0 kg Nha^{-1} and 225 kg Nha^{-1}, respectively, in cool season grasses (Power, 1984). Among forage crops, sorghum and maize, (C4 plants and tropical forages) maximised CWP for the summer season, together with one temperate grass: annual ryegrass (Callow *et al.*, 2004).

The world's major food crops are also reported to have high CWP, at the forage biomass, compared to tuber or grain biomass (Anderson *et al.*, 2003). The CWP for the forage biomass increases with old cultivars compared to modern cultivars (Siddique *et al.*, 2001), because modern cultivars were either bred for high CWP or NUE (Zebarth *et al.*, 2008). Crop water productivity for wheat grain is 5.2 – 10.8 kgha^{-1} mm^{-1} and 23.5 – 28 kgDM ha mm^{-1} for wheat forage biomass in China (Zhang *et al.*, 1999; Zhang *et al.*, 2005). However, a high CWP range of 4.8 - 12.1 (kgha^{-1}mm^{-1}) for grain and 16.1 – 37 kgDM ha mm^{-1}for forage biomass has been reported in Australia (French *et al.,* 1984). Maize grain ranges from 14 – 20 kg ha mm^{-1}; maize forage biomass ranges between 28 - 34 kgDM ha mm^{-1}; rice ranges between 7.1 – 8.1 kgDM ha mm^{-1} (Zhang *et al.,* 2005); grain legumes range between 2.5 - 15.9 kg ha mm^{-1} and 11.7 - 38.7 kgDM ha mm^{-1} for forage biomass (Siddique *et al.,* 2001); and potato tuber ranges from 62 - 116 kg ha mm^{-1}(FAO, 2009). The CWP of pasture is benchmarked at 20 kgDM/ha/mm, with a range from 0.7 to 21 kgDM/ha/mm in New Zealand (Martin *et al.,* 2006). The CWP review suggests that grain legumes have low CWP and potato a C3 plant, has the highest CWP amongst some of the world's major crops.

2.2.2.2 Crop-water production function and irrigation water use efficiency

Irrigation management is rational when all benefits (rather than yields alone) are maximised (English *et al.*, 2003). Total benefits are measured by the increased net yield and income per irrigation increase, the relief of environmental influence and production costs. Studies have shown that optimisation of total benefits depends on the crop yield relationship with water inputs: that is, crop-water production function (Geerts *et al.,* 2009). Crop water production function works as a tool for assessing profitable consequences and for making decisions on strategies for water management, when water is scarce (Igbadun *et al.*, 2007).

The relationship of applied water to yield (water production function) is curvilinear (Fig. 2.1), due to several water losses through run-off, surface evaporation, deep percolation and excessive water use. Figure 2.1 deduces that water supply from rainfall in section A are insufficient for maximum yield, as a result water productivity is low and curve shape is more like convex or quadratic. There is need to increase water supply through irrigation up to Section B. Sufficient application of water in section B results in increased yield and water productivity with less yield loss or water loss, resulting into a linear curve (Geerts *et al.,* 2009). Further increase of water supply increase tuber yield at a decreasing rate or with small margin thereby decreasing water procuctivity as described by section C in figure 2.1. Growers do not require applying water more than ETc after section B to achieve a good ET-Yield relationship.

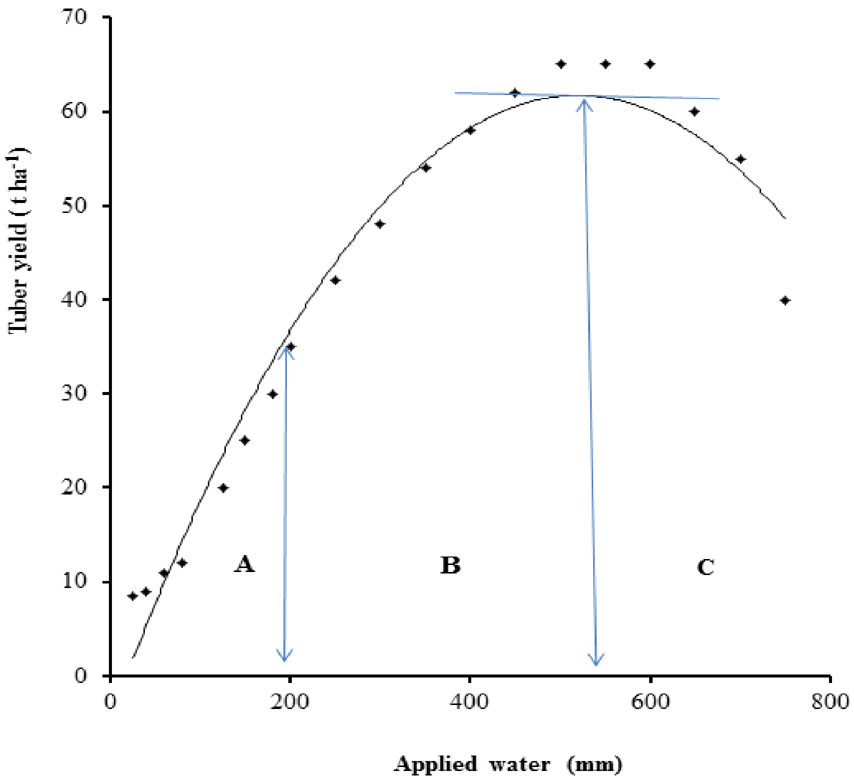


Figure 2.1 Schematic diagram illustrating water production function (A - C) and crop water production function (A - B) concept for potato.

The ET-yield relationship (crop water production function) is reported to be linear because increase of crop water consumption increases tuber yield at an increasing rate up to optimum production (English *et al.*, 2003; Kasyap *et al.*, 2002). However, Ferreira *et al.* (2007) has reported both relationships to be linear in potato, where the yield response to applied water (52 - 91 kg ha mm^{-1}) and ET-yield (62 - 105 kg ha mm^{-1}) varied with N fertilisation. The performance of the crop water production function was a result of appropriate N and water management. It has also been reported that the selection of crop cultivars with high efficiency in water use; the use of efficient irrigation technologie; and the application of less water during crop production (deficit irrigation), increases maximisation of total benefits from irrigation (Kirda *et al.*, 2002).

Efficient crops in water use and irrigation scheduling increase the slope of the ET-Yield thus IWUE. Efficient irrigation technologies minimise water loss to the equivalent evapotranspiration curve: that is, irrigation efficiency (IE). However, optimisation by water deficit, on its own, can reduce yield per unit area, despite efficient production costs and environmental management, in addition to low water use, per yield. The combination of cultivars, novel technologies and soil fertility strategies can increase both yield per unit area and per unit of water, simultaneously. The integration of efficient water use strategies provides primary water management strategies, which can reduce water use inefficiencies within a range of irrigation management and crop or cultivar categories by capturing leakages of water loss — which could not be tackled through the use of only one novel method.

Irrigation water use efficiency is defined as a marginal increase in total tuber yield, as a result of one extra unit of irrigation water (m^3). Irrigation water use efficiency (IWUE) is determined as the total yield difference between irrigation and the rain-fed crop, divided by the net evapotranspiration for irrigated crops, according to Howell (2001) as presented in Equation 2.1: where Y_i is the yield and ET_i is the ET for irrigation level i, Y_d is the yield and ET_d is the ET for equivalent water in the rain-fed plot: and I_i is the amount of irrigation applied for irrigation level i. Irrigation WUE, as a tool, evaluates the relative advantages of irrigation management to a rain-fed production system or crop cultivars.

$$\text{IWUE} = \frac{Yi-Yd}{Ii} \; or \; \frac{Yi-Yd}{ETi-ETd} \qquad \text{Equation 2.1}$$

2.2.2.3 Economic water productivity

Hoekstra *et al.* (2009) indicated that efficient water use is rarely achieved in agriculture, because water prices are lower than their real economic value. In addition, water is not privately owned and there has been a failure to cost the externalities that water users cause to the environment. In practice, assessment of the economic impact of a water footprint is difficult. Therefore, the cash per volume of water used and economic loss of not using the most competent crop cultivar or technology, for water saving, is assessed by economic water productivity (Molden *et al.*, 2001) and economic water loss per unit of water used (EWL), respectively. Economic water productivity and EWL are used as partial economic analysis of efficient water use strategies in Agriculture (Hoekstra *et al.*, 2009).

Economic water productivity (NZ\$/m^3) is estimated as the overall present value of each crop's marketable produce (NZ\$), divided by the actual volume of water (m^3) consumed by the plant (Molden *et al.*, 2001). The economic loss, per water unit used in producing an economic yield, is determined by multiplying the product price by the difference between the potential water productivity and the actual water productivity of that particular product (Chapagain *et al.*, 2005; Hoekstra *et al.*, 2009). Hoekstra *et al.* (2009) assumed that potential WUE and actual WUE have the same cost and water saved can be re-allocated to produce more of the same crop variety: and the price of the product is not variable. However, this thesis uses economic water productivity or cash per volume of water used for production (Aldaya *et al.*, 2008) only because it was difficult to identify potential CWP for all studied heritage crop cultivars.

2.2.3 Water footprint or virtual water content (m^3 $tonne^{-1}$) of growing crops

Virtual water content, as defined by Hoekstra (2003), is the amount of water required to produce the product at a place and time, where or when the product is needed. The water footprint refers to the cumulative volume of water needed for growing a unit of crop biomass (m^3 $tonne^{-1}$) (Hoekstra *et al.*, 2007; Hoekstra *et al.*, 2002). These two terms are sometimes used interchangeably and they are both important when assessing how much water will be saved, when producing a particular crop instead of producing an alternative crop. Both terms indicate the production method which has the least burden on the environment (Hoekstra *et al.*, 2003). Virtual water content (VWC) is more concerned with food production and trade at the point of consumption (Renault *et al.*, 2002). Water footprint (WF) is more associated with food production and environment at the point of production.

Values of water footprints (m^3 $tonne^{-1}$) are influenced by the same factors that affect CWP. However, water footprint is different from CWP because it is subdivided into three components: consumption of rainwater (green water footprint); surface or groundwater (blue water footprint); and volume of water required to absorb pollution (grey water footprint), which includes both direct and indirect water use (Hoekstra *et al.*, 2009). The sum of these components is the total water footprint, whereas the sum of the green and blue water footprint is the consumptive water footprint. The CWP determination hardly includes the grey water footprint, or the separate components of green and blue water. It only includes consumptive water (blue and green water) as a single component. The consumptive water footprint is inversely related to CWP.

Globally, the consumptive water footprint for irrigated crops is smaller than that for rain-fed crops, due to yield increase as a result of irrigation (Mekonnen *et al.,* 2010a). It has also been found by Mekonnen *et al.* (2010b) that a complete rain-fed agriculture is comprised of 91% green and 9% grey water, whilst supplementary irrigated crops have 48% green, 40% blue and 12% grey water, and the consumptive water footprint is comprised of 78% green and 12% blue water.

2.2.3.1 Typical water footprint and virtual water content for a range of crop categories

The value of a typical water footprint and virtual water content for crops depends on the harvestable product and whether it is related to the edible part, oil extraction or total biomass. Recent studies have shown that crops grown for food have a lower water footprint than crops specifically grown for energy and for oilseeds (Gerbens-Leenesa *et al.,* 2009a). Gerbens-Leenesa *et al.* (2009b) found that the average water footprint of growing crops for biomass production, in four countries, was lowest in potato (120 m^3 $tonne^{-1}$) and sugar beet (163 m^3 $tonne^{-1}$), whereas cotton (3494 m^3 $tonne^{-1}$) and soybean (2265 m^3 $tonne^{-1}$) were reported to have the highest water footprint. The water footprint of growing primary crops was found to increase for sugar crops (200 m^3 $tonne^{-1}$), vegetable (300 m^3 $tonne^{-1}$), tuber crops (400 m^3 $tonne^{-1}$), fruits (1000 m^3 $tonne^{-1}$), cereals (1600 m^3 $tonne^{-1}$), oilseed crops (2400 m^3 $tonne^{-1}$) and pulses (4000 m^3 $tonne^{-1}$), according to Mekonnen *et al.* (2010b).

There is spatial variation in the water footprint for producing the same crop, as reported by various scientists from different parts of the world. On average, sugarcane and potato have a small water footprint, whereas soybean requires more water to produce one tonne (Hoekstra *et al.*, 2003). The water footprint (WF) of growing potato ranges from 160 – 250 m^3 $tonne^{-1}$. (Hoekstra *et al.,* 2003; Zimmer *et al.,* 2003; Kumar *et al.,* 2007); WF of wheat ranges from 1150 – 2000 m^3 $tonne^{-1}$ (Hoekstra *et al.,* 2003; Zimmer *et al.,* 2003;Chapagain *et al.,* 2005); WF of rice ranges from 1400 - 3600 m^3 $tonne^{-1}$ (Hoekstra *et al.,* 2003; Zimmer *et al.,* 2003; Chapagain *et al.,* 2006); WF of maize ranges from 450 - 1900 m^3 $tonne^{-1}$; soyabean ranges from 2300 – 4000 m^3 $tonne^{-1}$ (Hoekstra *et al.,* 2003; Zimmer *et al.,* 2003; Kumar *et al.,* 2007); WF of pumpkin ranges from 238 - 240 m^3 $tonne^{-1}$; Kumar *et al.,* 2007); and WF of sugarcane ranges from 150 - 200 m^3 $tonne^{-1}$ (Kumar *et al.,* 2007; Mekonnen *et al.,* 2010a). The review shows that WF is lowest in potato and sugar cane and highest in soyabean and cotton. However, the wide variation in WF suggests a need for further measurements, in order to enhance general WUE in areas with a spatially high water footprint.

2.2.4 Nitrogen use efficiency

Nitrogen use efficiency (NUE) for potatoes is defined as the ratio of tuber yield to the amount of N applied for its production (Battilani *et al.,* 2004; Darwish *et al.,* 2006). It has been documented that NUE increases with restricted N application, whilst maximum N application reduces NUE in potato (Zebarth *et al.,* 2008; Darwish *et al.,* 2006). Irrigation is said to enhance NUE in potato compared to water stress, whilst an N increase also increases WUE, because WUE and NUE are positively and linearly related (Battilani *et al.,* 2004). However, improvement of NUE is also challenged by the way agronomic and physiological features are integrated, in addition to genetic approaches to achieving efficiency in nitrogen use (Hirel *et al.,* 2007).

2.3 Soil–Plant–Atmospheric Continuum (SPAC) and Physiological WUE

2.3.1 Plant water uptake and soil or root system

Agriculture, as a human activity, disturbs and modifies the nature of the plant ecosystem, in order to meet man’s interest. The sustainability of such plant ecosystems is only possible with proper management of soil, water and nutrient balances, in response to the atmosphere and its climate components, within a modified system, (Raes *et al.,* 2009). Naturally, the plant - water system within the ecosystem has water moving from the soil → root → stem → leaf → atmosphere, thus forming a continuous column of water called the soil-plant-atmospheric continuum (SPAC), with stomatal and non-stomatal controlling mechanisms (Phillip, 1966; Rose, 1996)**.** Subsequently, the physiology of WUE (within the SPAC) primarily depends on the leaf stomata, which responds to the atmosphere and soil environment, as a main regulation point for transpiration in plants (Raes *et al.,* 2009).

2.3.1.1 Stomata conductance response to atmosphere and soil environment

Stomata conductance (g_s) is an essential physiological characteristic associated with crop production. Stomata conductance (g_s) mainly regulates photosynthesis (A_n) and transpiration (T), depending on the environmental factors (Wright *et al.,* 2008). High leaf temperature raises atmospheric vapour pressure deficits, which then induces stomatal conductance (Sinclair *et al.,* 1984). The implication of a high water vapour gradient results in leaf water deficits, thereby, declining A_n and T rate (Bunce, 2003). It has been asserted that optimal stomatal opening for A_n is induced by high photosynthetically active radiation (PAR) and optimal soil moisture: whereas its closure is induced by high leaf water potential approached after maximum leaf transpiration and water deficits (Vos *et al.*, 1987).

Water deficits in the soil and atmosphere always affect the SPAC, thus causing the leaf stomata to close and thereby reducing carbon dioxide entry for photosynthesis (Weatherley, 1976). The stomatal closure is the primary constraint to A_n and T caused by mild to moderate water stress. This is initially signified by g_s, and internal carbon concentration (Ci) declines with mild or moderate water stress. The progressive build-up in water stress results in secondary restrictions to A_n in C3 and C4 plants, caused by an integration of stomatal and mesophyll conductance (Flexas *et al.,* 2002; Ripley *et al.,* 2010) and biochemical mechanisms (Galmés *et al.,* 2007). The mesophyllic limitation is envisioned by low stomatal aperture, without affecting Ci (Schapendonk *et al.,* 1989).

The literature confirms potato genetic differences in stomata resistances, leaf area index, canopy expansion and photosynthetic WUE, when the plant is exposed to different atmospheric water demands and soil moisture (Jefferies *et al.,* 1993b). The gaseous exchange in potato are reported to greatly differ with leaf age (Vos *et al.,* 1987; Ghosh, *et al.,* 2000), genotypes (Tekalign *et al.,* 2005), irrigation (Ahmadi *et al.,* 2010), nitrogen (Ghosh *et al.,* 2000; Olesinski *et al.,* 1989), and climate factors. Severe water stress is accelerated by high leaf vapour pressure deficit (VPD) (Bunce, 2003).

Galmes *et al.* (2007) investigated constraints to photosynthesis in C3 plants under water deficit and discovered that stomatal and mesophyll conductance were the major limiting factors, whereas the biochemical effect was insignificant. His findings concur with

Flexas *et al.* (2002) who reiterated that restrictions to photosynthesis become rigorous with water stress increase. On the other hand, the consequence of stomatal or mesophyllic restrictions to photosynthesis vary: stomata closure by water stress is said to improve photosynthetic WUE, by reducing transpiration more than photosynthesis, whilst mesophyllic activity does not affect photosynthetic WUE in potato, since both transpiration and net photosynthesis declines (Schapendonk *et al.,* 1989). Photosynthesis resumption, after severe water stress, depends on the resilience of each genotype (Galmes *et al.,* 2007).

Optimal water and N increases A_n, T and photosynthetic WUE in potato (Ghosh *et al.*, 2000). In another study, Ahmadi *et al.* (2010) found similar high potato A_n between full irrigation (FI) and partial root-zone drying (PRD), but low A_n with deficit irrigation (DI), as also observed by Liu *et al.* (2006b). These results demonstrate that A_n is greatly restricted by severe water stress in potato, as once reported by Vos *et al.* (1989ab). The photosynthetic WUE of PRD was found to be greater than DI and FI, thus confirming the sparing water use in PRD. In contrast, Liu *et al.* (2006b) found photosynthetic WUE and WUE to be similar between FI and PRD, but lower in DI, thus contradicting the statement that PRD has high photosynthetic WUE, compared to FI (Ahmadi *et al.*, 2010; Kang *et al.*, 2004). Liu *et al.* (2006a) reported a reduction in potato dry matter production and photosynthetic WUE with deficit irrigation, thus confirming that water stress decreases potato production, as observed by Wolfe *et al*. (1983). The review confirms that water stress restricts WUE on biomass and photosynthetic basis in potato and in other C3 plants and that water stress effects may vary with cultivars and different soil types.

2.3.1.2 Soil media

The soil conducts and contains water and nutrients, depending on its hydraulic characteristics. Usually, plants close their stomata when the amount of water in the soil media is nearly at wilting point (1500 kPa), and they open the stomata when the amount of water is readily available at field capacity (10-33 kPa) (Ahuja *et al.*, 1990; Scotter, 1977; Sumanasena, 2003). The field capacity in New Zealand is estimated as being from 4.9 to 10 kPa (Sumanasena, 2003). Globally, the optimum soil water tension, for potato, is between 5 kPa and 33 kPa (Shock *et al.*, 2007). Nevertheless, the maximum water holding capacity for soil media depends on its hydraulic conductivity, plant root zone depth for the crop cultivars being cultivated and the amount of water in the supply.

A well-developed root-zone enhances the roots to respond to the atmospheric demand: and it regulates the plant shoots, during a crisis of water stress, so that the stomata can keep the water in balance within the plant (Hoogland *et al.,* 1981). Nevertheless, potato roots are very shallow and less dense for tapping deep soil water (Hoogland *et al.,* 1981; Shock *et al.,* 2007). Consequently, a water deficit instantly lowers the physiological WUE in potato, as discussed above. Similar to any plant, potato is well coordinated (through roots, shoots and stomata) to soil water balance situations in the soil and atmospheric demand called potential evapotranspiration (ETp).

2.3.2 Evapotranspiration and irrigation requirements

The available soil water supports plant transpiration and root water uptake, in order to meet potential evapotranspiration demand (Monteith *et al.,* 1986). Potential evapotranspiration (ETp) refers to the volume of water that a crop could have consumed, if the water resource was adequate, whilst net water use for a crop is referred to as the actual crop evapotranspiration (ETc) (Pidwirny, 2006). In reality, potential crop water use is equivalent to crop evapotranspiration: that is, the volume of water to be replaced, in order to meet potential potato yields (Allen *et al.,* 1998). Evapotranspiration, within the SPAC, is influenced by aerodynamic resistance, stomatal resistance, canopy resistance, radiation, temperature, and relative humidity (Allen *et al.,* 1998).

Evapotranspiration demand is reported to be equal to the plant root ability for water uptake, when it is equal to water uptake, translocation and transportation: but when evapotranspiration demand is above the root ability, the crop closes its stomata (Ziemer, 1979). The interaction between atmospheric demands, the water potential of the leaf, the resistance of water movement in the plant and the soil water potential, depends on the soil moisture (Phillip, 1966). The difference between the evapotranspiration demand (crop water requirement) and the water supply (rainfall plus capillary rise) to the potato roots is what is referred as the ‘net irrigation requirement for meeting potato evapotranspiration demand’ (FAO, 1997b)

Potato evapotranspiration differs with genotypes, location and season, however, Allen *et al.* (1998) documented that the seasonal potato ET_c ranges from 500 - 700 mm for maximum yield. The seasonal potato ET_c variation widens with the season, a humid winter recorded 250 - 312 mm, whilst a summer season was recorded at 380 - 584 mm (Bowen, 2003). Wright and Stark (1990) reported a maximum potato ET_c of 450 - 700 mm in the USA. In Turkey, potato ET_c was reported to vary between 226 - 473 mm and 166 - 391 mm under surface and sub-surface drip irrigation (Onder *et al.* 2005), whilst Erdem *et al.* (2006) reported ET_c of 673 mm and 524 mm for furrow and drip irrigation within Turkey. Kasyap *et al.* (2003) determined potato ET_c ranging between 164 - 280 mm in India, using 30 - 75% depletion irrigation scheduling, whilst Panigrahi *et al.* (2001) reported ET_c of 200 - 320 mm within India. Yuan *et al.* (2003) determined potato ET_c of 400 mm under drip irrigation in Japan. Potato evapotranspiration variations indicate that each location and genotype requires its own recommendation of ET_c, otherwise maximum yields may not be realised.

Crop evapotranspiration for New Zealand, especially in the eastern region, is expected to increase with climate variability (Kevin, 2001). The drought affected areas, or seasons, are expected to have a higher evaporative demand than the normal seasons (Mullan *et al.*, 2005). The summer drought is expected to increase the VPD and reduce the soil water content below field capacity. Summer drought will affect the SPAC of all crops in New Zealand (Kevin, 2001). Drought will increase water deficits by 50 - 250 mm potential evapotranspiration (ETp), with a maximum annual ETp of 300 - 500 mm, in the driest regions of New Zealand (Mullan *et al.*, 2005). The change in ETp is expected to increase irrigation by 55% for each decade (Mullan *et al.*, 2005; New Zealand govt., 2000). Broadly speaking, climate variability in New Zealand will result in more economic water scarcity than physical water scarcity (IMWI, 2002). The rise in pumping costs will reduce the profitability of irrigated crops, resulting into economic water scarcity.

Clothier *et al.* (2010) expressed concern that New Zealand is one of the countries that is showing a very high increase in total agricultural water use and irrigated areas, over the past decade. However, Australia has managed to increase its irrigated areas, despite a decrease in agricultural water use, due to efficient water use. The performance of Australia suggests that there are opportunities to reduce agricultural water use in New

Zealand, by following novel technologies (Clothier *et al.,* 2010). An understanding of alternative crops, crop genotypes and agronomic practices, which use water sparingly, is another priority for the adjustment to high evaporative demand, besides novel irrigation technologies. Taewa and other heritage crops are some of alternative crops that can contribute to sparing water use in New Zealand.

2.4 Taewa species and production trend in New Zealand

Taewa (*Solanum tuberosum*) is a collective name for all potatoes cultivated by Maori people in New Zealand since the 18th century (Roskruge, 1999). Taewa originated from South America in the region of Peru and Chile (Roskruge *et al.,* 2010). Maori people redomesticated it in New Zealand, either from early European explorer or trading vessels from South America. Taewa cultivars were then developed through potato seedling selection and selection of true potato seed from potato berry (Harris *et al.*, 1999; Harris, 2001). Taewa cultivars can be grouped into dark skin, multiple coloured, red skin, creamy, brown or light coloured skin and others with pink or white skin (Harris *et al.,* 1999). The commonest Taewa cultivars in New Zealand include: Hukaroro, Pawhero, Karuparera, Ngauteuteu, Raupi, Tutaekuri, Moe Moe and Wherowhero (Plate 2.1; Harris, 2001). Tutaekuri belong to *Solanum tuberosum subsp. andigena* Juz & Buk (Peruvian/Andean) while the other Taewa cultivars are *Solanum tuberosum subsp. tuberosum* L (Chilean) (Roskruge *et al.,* 2010).

Harris *et al.* (1999) outlined East Coast – East Bay of Plenty region and the Hawkes Bay, Wairarapa, Northland and Rangitikei as the main production area of Taewa in New Zealand in the early 19th Century. Taewa production among the Maori in these regions had enforced social-economic attributes on geneology and creation, kinship and family relationship, spirituality, hospitality and kindness, customs and habits, and economic survival (Roskruge, 1999). However, by 1998, Roskruge could not find more scientific information and production trends related to Taewa production (Roskruge, 1999). The main reason was that Taewa production among Maori did not receive enough support from New Zealand Government on disease and pest control compared to commercial farmers. Most of the Taewa cultivars were susceptible to leaf blight. Consequently, Taewa production was the most affected during the 1905 – 1906 leaf blight epidemic (Harris *et al.*, 1999).

Taewa production trends are also scanty because most scientific research on Taewa is primarily social in nature, except the study by Roskruge, (1999), Hayward (2002) and Harris (2001). Taewa research since 1999 includes: (1) Taewa Maori : their management, social importance and commercial viability by Roskruge, (1999); (2) *Nga Riwai Maori- Maori potatoes* on an Ethnobotany basis by Harris (2001); (3) Effect of nitrogen and plant density on the growth and development of Taewa by Hayward (2002); (4) The contribution of Taewa (Maori potato) production to Maori sustainable development by McFarlane (2007); (5) The expansion of sustainability through New Economic Space: Māori potatoes and cultural resilience by Lambert (2008); and (6) The lifecycle and epidemiology of *Bactericera cockerelli* on three traditional Maori food sources by Puketapu (2010). These studies have established that Taewa is equally important as modern potato across New Zealand and Australia. Roskruge *et al.* (2010) indicated that the tough times and harsh environment that Taewa went through in the 19th century, made Taewa to be hardy and disease resistant. However, management and crop physiology characteristics are the setbacks impeding Taewa production (Roskruge, 1999; Roskruge *et al.*, 2010).

Taewa yield is physiologically handcapped by its tuber number and tuber size characteristics. Taewa cultivars of Kowiriwiri, Tutaekuri were reported to have late establishment and low tuber yield compared to commercial cultivars of Red King Edward and Ilam Hardy (Roskruge, 1999). Ilam hardy yielded 1.8 kg/plant as compared to Tutaekuri with 0.92 kg/plant. A followup study by Roskruge (1999) on ten Taewa cultivars, tuber yield ranged from 1.04 kg/plant to 1.8 kg/plant. Moe Moe had the highest tuber yield among Taewa but lower than Red King Edward. Harris (2001) also reported that Rua, a commercial cultivar yielded 1.52 kg/plant compared to Taewa with 0.74 kg/plant. Hayward (2002) also studied Kowiriwiri, Tutaekuri, Matariki and Moe Moe in comparison with modern cultivar, Red King Edward. Tuber yields were highest in Moe Moe (4.5kg/plant) and lowest in Matariki (2.4kg/plant). The commercial cultivar, Red King Edward was outyielded by Moe Moe suggesting possibility of higher potential yield in some Taewa cultivars than commercial cultivars.

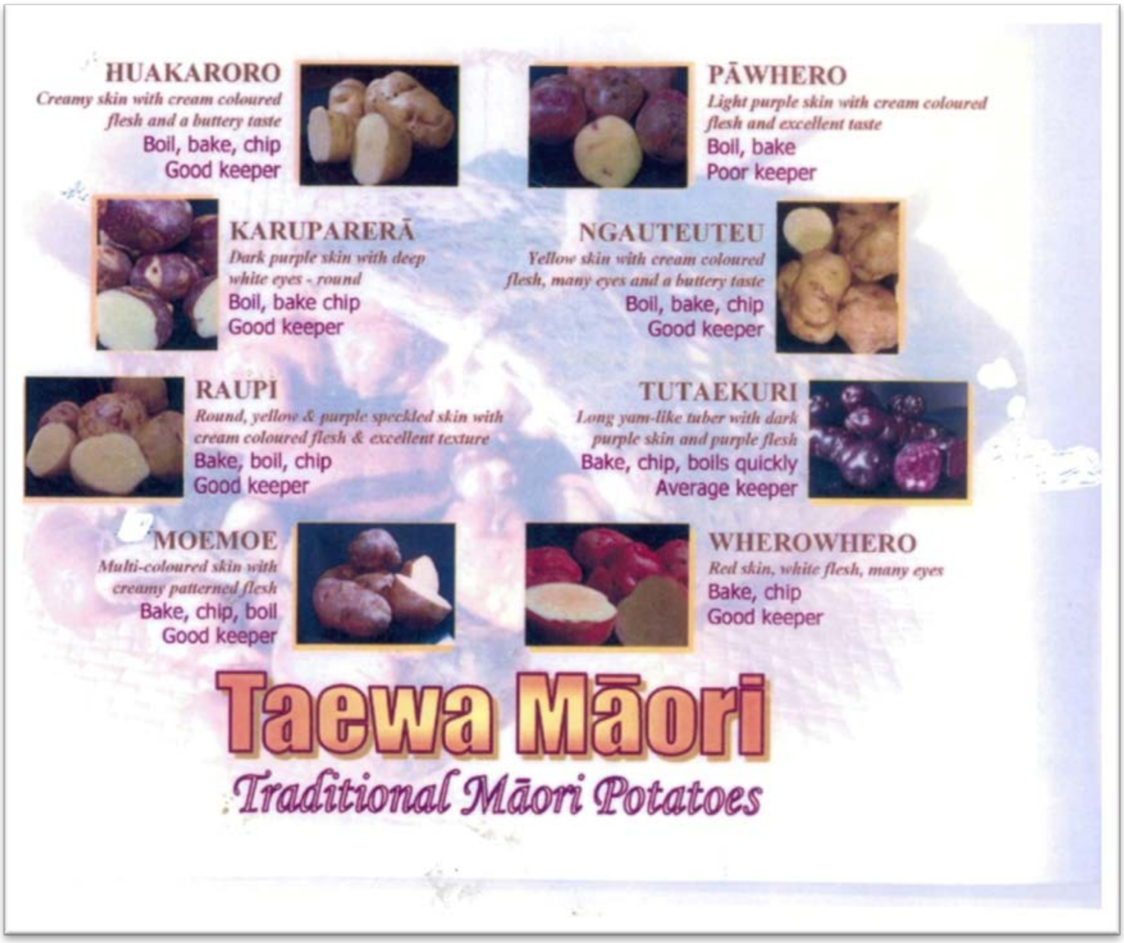


Plate 2.1 Varieities of traditional Maori potatoes (Taewa) in New Zealand sourced from Roskruge, N, Massey University, 2012

The high number of tubers of small size in Taewa and traditional management methods practiced by Maori were alleged to be the main cause of lower tuber yields in Taewa (Roskruge, 1999; Roskruge *et al.*, 2010). On the other hand, Taewa has great business potential because of its easiness to grow and potential commercial attributes due to the people's growing interest in traditional crops at national and internation market. Methods for seed selection and disease control applied by Taewa growers were reported to be unscientific (Walker, 1997). These methods and lack of irrigaton in most Taewa production system and viruses have contributed to low Taewa tuber yields (Roskruge, 1999). Strategies for maximising crop water and nitrogen productivity or breeding for high productivity that was employed in modern potato cultivars was not consistent with heritage potato, Taewa.

2.5 Strategies and constraints for maximising crop water and nitrogen productivity in modern production systems

2.5.1 Opportunities for maximising WUE in agriculture

Water use efficiency in agriculture is maximised through innovative irrigation and biological water-saving technologies : deficit irrigation (English *et al.*, 1996), partial root zone drying (Wang *et al.*, 2009b), drip irrigation, the use of crops with high water to biomass conversion ability (McLaughlin, 1985; Steyn *et al.*, 1998), agronomic measures, including irrigation scheduling (varied irrigation) (Hedley *et al.*, 2009ab), mulching, fertilisation and conservation farming, in relation to crop cultivar selection (Zhang *et al.*, 2005).

The emphasis for this review is on how cultivars and agronomic measures of irrigation and N management enhance WUE in agriculture. Morison *et al.* (2007) established that crops which transpire and fix more carbon per unit of water — and those that allocate more assimilates toward the harvestable yield — provide more opportunities for maximising WUE, than others within the same management and environment. Furthermore, non-water input (fertilisation and cultivar selection) and irrigation factors integrate well together, in order to capture optimum water for transpiration (Morison *et al.*, 2007) and strengthen the sink (Viets, 1962). These opportunities suggest a balance of input factors in agriculture, or otherwise, the deficit in one factor can reduce leaf expansion (Jefferies *et al.*, 1993a), resource use and transpiration (Imma Farre *et al.*, 2006; Tanner *et al.*, 1983). This observation supports the finding that WUE of potato in nutrient deficient soil is limited by transpiration, from reduced LAI and reduced allocation of biological assimilates into the sink (Jefferies *et al.*, 1993b).

Transpiration and LAI are related. An increase in the canopy increases crop water use, whilst decreasing evaporation (Ritchie, 1983). Evapotranspiration only relies on soil surface prior to the development of a full canopy but (as the canopy grows) evaporation declines due to soil cover. One role of nitrogen (N), in this process, is the facilitation of fast growing roots and canopy establishment, in order to enhance the WUE, which depends on soil water storage. WUE which is met by decreasing evaporation or runoff whilst increasing soil water storage, increases total production per unit of water available for agricultural use. However, it does not increase biomass production per unit of water evaporated from the same area (Tanner *et al.*, 1983). With the limits of course, the greater the transpiration, the greater the total photosynthesis, therefore the greater the plant production.

Water use efficiency, per unit of water available and evaporated from the same area, improves with high water productive genotypes and agronomic practices, which reduce evaporation (Howell, 2001; Sinclair *et al.*, 1984). This supports a deliberate change, from low water productive crops, to high water productive crops (Hoekstra *et al.*, 2007; McLaughlin, 1985). The optimal irrigation and fertilisation reported in rice (Zhang *et al.*, 2005) and potato are also the best means for increased water productivity (Darwish *et al.*, 2006). Furthermore, some indigenous and wild potato crops or cultivars (Zebarth *et al.*, 2004, 2008), wild oilseeds, jojoba (*Simmondsia chinensis* Schneider), guayule (*Parthenium argentatum* Gray) are also reported to reduce their water and nitrogen use, without a decline in their yields, under both rain-fed and irrigated conditions (McLaughlin, 1985). The variation in allocation and rate of assimilation offered by various heritage or old crop cultivars and agronomical strategies can provide alternatives for crop diversification, in times of water scarcity (Bessembinder *et al.*, 2005).

The substantial opportunities for maximising resource use in agriculture focus on a combination of strategies, which use the concept of ‘Water Use Efficiency (Barker *et al.*, 2003). In conclusion, the high yield and WUE apparent in most modern crop production systems relies on a combination of factors, including appropriate site selection, pest and disease control and optimum management of inputs, rather than just simple genetic improvement (Richards *et al.*, 2002).

2.5.2 Water and nitrogen management in modern potato production

Potato water requirements range from 400 - 800 mm (Ekanayake, 1989; Allen *et al.*, 1998; FAO, 2002), whilst N requirement is 235 Kg N ha^{-1}, within a 120 - 150 days growing period (Westerman, 2005). In New Zealand, Craighead *et al.* (2003) recommended 200 - 250 kg N ha^{-1} for main crop potatoes and 300 kg N ha^{-1}, where the season is very long. Winter potatoes were recommended at 160 - 240 kg N ha^{-1} for maximum yield and minimum N leaching. The N estimate for New Zealand has been confirmed by Martin *et al.* (2001), when they found no tuber yield increase with N over 242 kg N ha^{-1} at Pukehoke. However, most growers in New Zealand still use 400 kg N ha^{-1}. In Australia, N rates of 80 - 120 kg N ha^{-1} were recommended as sufficient rates for obtaining 80 - 350g tuber sizes, for crisp production (Dahlenburg *et al.*, 1990).

Sparrow *et al.* (2003) investigated Russet Burbank response to basal dressing up to 250 kgN ha^{-1} and top dressing up to 100 kg N ha^{-1} in Tasmania and found that top dressing did not enhance tuber yield, compared to basal rates. In another Australian study, Brown *et al.* (2008) found no difference between N side dressings (0, 125, 250, 500 kg N ha^{-1}) on tuber yield. They also found no significant N leaching with N up to 300 kg N ha^{-1}, because the potato removed 250 kg N ha^{-1}. Alva *et al.* (2009) recommended 112 + 112 kgN ha^{-1} for basal and top dressing in USA, respectively. The side dressing was recommended to be applied five times from four weeks from planting, at two week intervals, based on his N and reduced tillage research using a centre pivot irrigator (Alva *et al.*, 2009). Nitrogen recommendations are variable between and within countries, due to soil status and objectives.

Nitrogen is needed for growth *during* the first half of the growing season whilst N applied *later* is stored in the tuber (Belanger *et al.*, 2002). Darwish *et al.* (2006) also found that a lower N rate (125 kg N ha^{-1}) results in a satisfactory N uptake, compared to a high application (500 kg N ha^{-1}). Haverkort (2003) found that 200 kg N ha^{-1} was optimal: and any excess above that amount would decrease the tuber yields. This finding supports other findings which show a tuber yield decline with high rates in N application (Vos *et al.*, 1997) and water deficit (Martin *et al.* 1992).

Irrigation was recommended on a weekly basis during dry periods by Martin *et al.* (1992), to meet over 440 mm water requirement in New Zealand. Martin *et al.* (1992) also reported tuber yield reduction in potato with water deficit, as reported by Bowen (2003), Darwish *et al.* (2006), Kang *et al.* *(*2004) and Shock *et al.* (2007). Shock *et al.* (2007) recommended that growers needed to irrigate the correct amount of water at the correct time and also monitor soil moisture and agro-meteorological data, for precise potato irrigation. Maximum tuber yield and minimum land pollution can only be achieved when water use is near potential crop evapotranspiration. It has been reported that correct irrigation scheduling, using estimated evapotranspiration and soil water tension, optimises potato water use for maximum tuber yield (Shock *et al.*, 2007).

Water deficits of 65 - 70% of soil available and water and soil water potential of -25 kPa reduce marketable tuber yields by 31 - 68%, due to poor tuber quality and poor tuber weight (Shock *et al.*, 2007; Darwish *et al.*, 2006). Battilani *et al.* (2008) also reported that optimal moisture *without* N fertilisation — and N fertilisation *with* water deficit or excessive water — both decrease potato growth and tuber yields. Henceforth, the benefit of N on yield depends on the correct time and amount of water and N application (Haverkort, 2007).

Soil moisture and N availability also affects the choice of potato cultivars, because there are significant genotypic differences in response to water use (Laurence *et al.*, 1985; Steyn *et al.*, 1998). Sinclair *et al.* (1984) showed that some potato cultivars use water more efficiently, and some tolerate drought better than others (Steyn *et al.*,1998). In contrast, other findings report no significant variations between potato cultivars, in response to water and N supply (Dalla Costa *et al.*, 1997; Belanger *et al.*, 2002). In New Zealand, significant differences in yields between modern cultivars and Taewa, have also been reported (Harris *et al.*, 1999). However, Taewa has not been rated with modern cultivars on different water and N regimes. Hayward (2002) attempted to assess Taewa response to N and population density, but the study did not reach a clear conclusion.

2.5.2.1 Dry matter partitioning and tuber yield in response to irrigation and nitrogen

Growth and dry matter partitioning

Potato growth and partitioning of dry matter (DM) to leaves, stems, roots and tubers, vary with potato genotypes, water, N and growth stage (Geremew *et al.*, 2007). Partitioning to leaves, stems and tuber, within 50 - 60 days from planting, was reported to be similar (but varied over time) between newly released and old commercial cultivars in South Africa (Geremew *et al.*, 2007). Tuber formation between cultivars was found to be in three categories: early tuber set with rapid harvest index (HI) increase; early tuber set with slow HI increase; and late tuber set with gradual HI increase (Geremew *et al.*, 2007). Geremew *et al.* (2007) also observed a reduction in partitioning to tubers and tuber yield in cultivars with the highest canopy, LAI and DM, compared to cultivars with the least LAI, canopy and DM.

Errebhi *et al.* (1999) reported that commercial potato cultivars partitioned more to tubers, whereas wild potato allocated more to shoots: and their hybrids were intermediate. Commercial cultivars partitioned 1% (roots), 15% (shoots), 0% (fruits), 84% (tubers), whereas wild cultivars allocated 18% (roots), 52 % (shoots), 23% (fruits) and 7% (tubers): and their hybrids allocated 9% (roots), 39% (shoots), 14% (fruits) and 14% (tubers). Traditional barley cultivars (Abeledo *et al.,* 2011) and old wheat cultivars (Siddique *et al.,* 1990a) were also reported to optimise allocation of assimilates to non-harvestable products, compared to new modern cultivars. The review shows genotypic variation in dry matter partitioning and also that most traditional or old cultivars increase LAI and canopy development at the expense of harvestable products.

Tuber yield and WUE for modern potato

The average tuber yields for modern potato cultivars (e.g Moonlight, Dawn, Kamai, Karaka, White Delight, Driver and Pacific), during the time of their release, ranged from 38 to 55.4 t ha^{-1} in New Zealand (Anderson *et al.*, 2004; Genet et al., 1997; Genet *et al.,* 2001). Early studies by Craighead *et al.* (2003) reported a tuber yield increase from 50.3 to 52.4 t ha^{-1} in Ilam Hardy; 72.2 to 76 in Fiana; 50.5 to 50.6 in Kennebec; and 51.9 to 79.3 in Russet Burbank with N increase, from 150 to 300 kg N ha^{-1}. The other study on Russet Burbank yield ranged from 55.2 to 73.3 t ha^{-1}, in New Zealand. The highest tuber yield increase with N application was found in well watered and the lowest increase in drought plots (Martin *et al.,* 1992).

The yields for modern potato are double the current mean total and marketable tuber yields attained by Taewa growers, which range from 15 - 20 t ha^{-1} and 10 - 15 t ha^{-1}, respectively (Roskruge, pers. comm., 2011). The early studies on Taewa and modern potato cultivars presented in section 2.4 also proved that modern potato yield are more than twice the yield of Taewa (Roskruge, 1999; Harris *et al.,* 2001). The gap on average tuber yield and WUE between the world (with an average of 15.9 t ha^{-1}) and those reported across world experiments (with an average of 30 - 60 t ha^{-1}) is also reported to be very wide (Bowen, 2003; Sale, 1973). Such yield disparities are accelerated by climatic conditions, genotypes, soil and water management factors (Shock *et al.,* 2007).

The Asia and Pacific region also experiences an average potato yield gap. The average tuber yield is 15.7 t ha^{-1}, with the highest average yields ranging from 45.3 - 52 t ha^{-1} in New Zealand, and the lowest average tuber yields of 2.5 t ha^{-1} in Timor-Leste (Pandey, 2008). Worldwide experiments have confirmed that potato yields and WUE vary with location and management (Bélanger *et al.,* 2002; Darwish *et al.,* 2006; Ferreira *et al.,* 2007; Starr *et al.,* 2007). The average potato yields in New Zealand are also higher than those reported in many other countries.

Extraordinary tuber yields of 88 - 89 t ha^{-1} were reported by Kunkel, as quoted by Sale (1973). Brown *et al.* (2008) also reported yields of 75 - 80 t ha^{-1} in Australia. In New Zealand, Craighead *et al.* (1999) and Sinton (2007) reported potential yields of 80 t ha^{-1}. However, farmers only realise an average of 60 t ha$^{-1,}$ (40 - 80 t ha^{-1} in their main crop and 15 - 50 t ha^{-1} in the early crop). The failure to reach the potential tuber yield is caused by water and N stress (Sinton, 2007). Efficient management of water, N and genotypes, can reduce the tuber yield gap experienced in New Zealand and other parts of the world.

Sprinkler irrigation increases tuber yield of Ilam Hardy four-fold in New Zealand (Foot, 1974). Drip irrigation and fertigation also increases tuber yields and WUE of potato, compared to furrow irrigation (Janat, 2001; Starr *et al.,* 2007). In Turkey, Erdem *et al.* (2006) reported a WUE of 4.7 to 6.63 kg m^{-3} for furrow irrigation and 5.19 – 9.47 kg m^{-3} for drip irrigation, whilst Martin *et al.* (1992) reported a high WUE of 12.8 to 16.7 kg m^{-3}, under drip irrigation in New Zealand.

A study on irrigation of Agria potato cultivar in Iran, by Bahramloo *et al.* (2009), reported tuber yield and WUE decrease from 28.6 to 24.6 t ha^{-1} and 2.4 to 1.8 kg m^{-3}, respectively. The use of more water than 664 mm in full irrigation (1340 mm) was suspected to have declined the tuber yield and WUE. Subsequently, partial irrigation had a high IWUE of 13.2 kg m^{-3} (Bahramloo *et al.,* 2009). The majority of the results on efficient water use indicators in other countries may differ from New Zealand, due to weather differences. Nevertheless, this review indicates that potato has higher WUE and tuber yield potential than many crops and that there are genotypic variations in WUE (FAO, 2008; Kang *et al.,* 2004; Trebejo *et al.,* 1990). Despite improvement in potato yields, the gap between the actual yield and the potential yield is still very wide. The gap shows that potato potential yield in some cultivars is not yet fully exploited.

2.5.2.2 Tuber quality response to irrigation and nitrogen.

Potato tuber quality is assessed based on tuber dry matter (DM), specific gravity (SG), reduced sugar content, nutritional value and external tuber shape and size (Westermann *et al.*, 1994). Irrigation and N reduces SG and DM. The N effect on SG and DM is significantly higher with irrigation, compared to water stress (Lawrence *et al.*, 1985; Dahlenburg *et al.*, 1990). Dahlenburg *et al.* (1990) reported SG decreases with N increase, from 80 – 320 kgN ha^{-1}, where as N above 150 – 200 kg ha^{-1} reduced SG. Nitrogen also increases the cases of misshapen tubers, crisps colour and hollow hearts (Sparrow *et al.*, 2003). On the other hand, Belanger *et al.* (2002) reported a decrease of SG, with an N increase above 50 kg N ha^{-1}, under irrigation. Nitrogen increases the nitrate accumulation in the tubers, thereby declining SG (Belanger *et al.*, 2002). The effect of NO_3-N concentration (on stressed potato fertilised with high N), can be reduced by applications of water to avoid human risk (Belanger *et al.*, 2002 quoting Carter, 1974 and Beidmond, 1992). Cultivars with small tubers had more N concentration than the large tubers, because tuber increase enhanced the starch pool (Logan, 1989) and protein decreased it (Belanger *et al.*, 2002). Late maturing cultivars have also been reported as having greater SG than early maturing cultivars (Belanger *et al.*, 2002).

Similarly, sugar concentration in potato tuber increased above an acceptable range, with N increase (Dahlenburg *et al.*, 1990). The reduction of sugar content in potato tubers according to Logan, (1989) is not influenced by irrigation or N. However, other research on sweet potato (*Impomea batatus*), by Ekanayake *et al.* (2004), reported that irrigation significantly reduced the levels of reduced sugars with genotype and irrigation interaction. Singh *et al.* (2008) compared Taewa and modern cultivars' quality characteristics and found that Taewa (Moe Moe and Tutaekuri) had higher DM and SG than modern cultivars, in New Zealand. However, Taewa quality was not assessed at varied N and irrigation, in order to identify the potential of potato quality in Taewa with different agronomical practices.

2.5.2.3 Sustainable land use implications in relation to irrigated and N fertilised potato

Agricultural sustainability is described in terms of the indefinite provision of environmental, economic and social well-being benefits, with minimum negative externalities (MacLeod *et al.*, 2006). In the case of this review, sustainable land and water use refers to the maximisation of returns from land and water use, whilst environmental pollution is minimised. Water use efficiency is taken as a generic indicator for the implementation of sustainable crop intensification and diversification programmes and policies (Ford *et al.*, 2009; Miskell, 2009). Crop intensification and diversification are possible ways of adapting the agricultural system to the population growth, urbanisation and climate change challenges (Fowler, 1999). However, these strategies (crop intensification and diversification) involve irrigation, heavy pesticide and herbicide use and fertilisers, which pollute the environment (Jalali, 2005; Power *et al.*, 1989).

Study shows that high use of N fertilizer (without any consideration of the residue remains of the previous winter greens) has increased nitrate accumulation in New Zealand, (Francis *et al.*, 2003; Thomas *et al.*, 2004). Potato production (apart from dairy production) is the most inefficient land use system in terms of N loss in New Zealand (Francis *et al.*, 2003; Sumanasena, 2003; Thomas *et al.*, 2004). This system registers high nitrate leaching (Francis *et al.*, 2003; MAF, 2002), due to high fertiliser application. Furthermore, over-irrigation flushes the nitrate-N beneath the root zone, thus causing groundwater contamination above a nitrate threshold set at 11.3 mg L^{-1} in New Zealand (Ministry of Health, 1995, cited in Sumanasena, 2003). Irrigation and N management in potato require consideration of ways to realise environmental, social and economic objectives, in addition to sustainability in agriculture, as recommended by MacLeod *et al*. (2006).

2.5.3 Effects of mechanical and hormonal canopy manipulation on yield and WUE

Growth regulators perform a key role in potato tuberization under the control of specific stimuli (Chapman 1958; Kumar *et al.,* 1973). Major hormones reported enhancing tuberisation and growth include: cytokinin, indole-3-acetic acid (IAA) and ethylene, gibberellic acid (GA), abscissic acid (ABA) and auxin (Vreugdenhil *et al.,* 1989). Gibberellic acid hinders tuber formation by promoting stolon elongation whilst the other hormones promote tuber formation by counteracting GA at different tuber formation stages (Vreugdenhil *et al.*, 1989). Gibberellic acid is always artificially counteracted by foliar application of chlorocholine chloride (Wang *et al.,* 2009a; 2010).

Chlorocholine chloride (CCC) is the usual name for chlormequat chloride (also known by trade name as Cycocel). Chlorocholine chloride is one of the prominent bio-regulatory hormones that control excessive plant growth, in order to improve the root system. Chlorocholine chloride is chemically known as 2-thloroethylthrimethyl ammonium chloride with a molecular formula of $C_5H_{13}C_{12}N$. Chlorocholine chloride significantly retards above-ground growth in potato. Chlorocholine chloride also enhances the photosynthetic capacity of potato and photo-assimilates partitioning into tubers, thereby boosting tuber growth (Wang *et al.,* 2009a). Wang *et al.,* (2009a) reported that foliar spray of CCC to potato increased IAA whilst decreasing ABA content. The study by Wang *et al.,* (2009a) found that IAA counteracted gibberellic acid. The study by Xu *et al.,* (1998) also found that ABA counteracted gibberellic acid for tuberisation. Vreugdenhil *et al.,* (1989) concluded that gibberellic acid is the main controller of tuber formation under the regulation of ABA, IAA and other hormones such as cytokinin and auxin which influence tuber size. However, IAA has a significant role in initiating tuber formation by retarding stolon elongation under both inducing and no-inducing environmental conditions (Xu *et al.,* 1998).

Soil mechanical resistance (dryness, low porosity and root penetration) to plant roots stimulates Indole-3-acetic acid (IAA) to produce ethylene (Vreugdenhil *et al.,* 1989). The responsibility of ethylene in tuber formation in potato is short lived, but it facilitates other hormones (cytokinin, ABA) to carry on the tuber formation and development. It has been reported that some stimuli that induces this tuber formation includes grafting and short days (Kumar, 1973) and topping (Hossain *et al.,* 1992*)*, and it is hormonal in nature (Kumar, 1973). Nevertheless, the effect of topping on endogenous hormones, water use and tuber yield in potato has little literature in New Zealand and worldwide.

Studies on leaf canopy manipulation have shown that the alteration of a large leaf canopy reduces water use, whilst increasing tuber yield. Water use reduction, photosynthesis and yield improvement were reported in wheat (Richards, 1983) and potato with growth hormones and topping (Rex, 1992; Wang *et al.*, 2009a, 2010). The review did not identify any canopy manipulation work on potato in New Zealand. However, results from different parts of the globe show that mechanical and hormonal canopy manipulation enhances tuber yield and WUE, through dry matter redistribution and photosynthesis improvement (Rex, 1992; Wang *et al.,* 2009a, 2010).

2.5.4 Challenges and limitations to maximisation of WUE in arable crops

The options for increasing water productivity in agriculture are accompanied by several challenges and limitations (Kijne *et al.*, 2003), because improvement to marketable yield is required to be met with reduced transpiration and reduced outflow at farm level, whilst still increasing the economic productivity of all sources of water (Kijne *et al.*, 2003). Issues of global warming and climate change are expected to instigate unexpected or unplanned water use by plants, due to expected increases in temperatures and VPD (Mullan *et al.*, 2005; Kevin, 2001). The main challenge is that the demand for water use is increasing, when attempts are being made to reduce water footprints and greenhouse gas emissions, at the same time as attempts are being made to produce sufficient food for the world’s increasing population.

Issues relating to efficient water use in agriculture are rarely accompanied by economic incentives (Hoekstra *et al.*, 2009). For instance, the lack of actual economic value of water saving or loss in agriculture was also asserted by Zoebl (2006). Water footprint calculation based on hypothetical crop and water use (Maes, 2009) and failure of growers to pay for diffuse discharge limit economic water scarcity resolutions. Issues relating to efficient crop cultivars are also challenged by social and political acceptance as well as pests and disease infestation. Sometimes such crops may have low economic value, low yields or poor taste despite being efficient in resource use. These shortfalls greatly limit the adoption of water saving concepts. Consequently, normal WUE indicators may not easily apply to such unanticipated water demand. This is the reason why the WUE concept requires integrated techniques and tools, in order to support decisions relating to water allocation for specific crops and locations (Bessembinder *et al.*, 2005), such as those found in New Zealand. Integral techniques offer more accurate results to counteract the challenges and limitations to optimization of WUE in potato, especially with the recent outbreaks of Tomato Potato Psyllid (TPP).

2.5.5 Tomato Potato Psyllid

Tomato Potato Psyllid (TPP) (*Bactericera cockerelli*) is a new pest for potatoes and tomatoes that arrived in New Zealand in May, 2006 from North America (Thomas *et al.*, 2011). TPP is a vector of bacterium pathogen "*Candidatus* Libaribacter solanacearum" which causes Zebra chip disease in potato (Thomas *et al.*, 2011). TPP causes great challenges and limitations to maximisation of WUE in modern and heritage potatoes in New Zealand because of its devastating impact on tuber yield and quality (Teulon *et al.*, 2009). Teulon *et al.* (2009) and Pukehuke, (2010) stated that there is a substantial economic yield loss being caused by TPP in modern potatoes, tomatoes and Taewa. TPP attack reduces tuber number, tuber size and production of secondary tubers in potato and therefore reduces economic yield if not properly controlled.

Studies on the biological and chemical control of TPP in New Zealand are promising to find a means of controlling TPP. The natural biological agents includes *Micromus tasmaniae* and *Melanostoma fasciatum* (Walker *et al.,* 2011) while *Tamarixia trizae* (Burks) was introduced as biological agent from Mexico, (Workman & Whiteman, 2009). Page *et al.* (2011) found abamectin + oil and bifenthrin as effective pesticides for reducing adult TPP up to 3 days after treatment while thiacloprid, spiromesifen, imidacloprid, spinetoram and azadrachtin were found to be slightly toxic. However, Page *et al.* (2011) recommended that TPP nymphs are best controlled with abamectin + oil, spirotetramat, bifenthrin and spiromesifen. In an earlier study by Berry *et al.*, (2009) TPP nymphs were recorded dying 48 h after spraying with dichlorvos, lambda-cyhalothrin, methomyl, taufluvalinate, methamidophos and abamectin while applications of azadirachtin, spiromesifen, abamectin, spirotetramat and thiacloprid gave 82-100% mortality, while buprofezin, pymetrozine and imidacloprid application gave 36-53% mortality after 168 h. An integral point of TPP biological and chemical control is monitoring TPP populations, and the control of further introductions by New Zealand Government (Walker *et al.* 2011).

2.6 Summary and conclusion

The literature review shows that WUE is either expressed as a generic term for appraising water saving technologies (water footprint), or as a specific key indicator for appraising crop water productivity: that is, biomass per volume of water used or cash per volume of water used. Water use efficiency, expressed in a specific term also known as CWP, does not estimate environmental pollution (grey water components), whilst a water footprint, as the generic WUE indicator, estimates environment pollution (grey water) and water consumption from surface or ground (blue water) and from rainfall (green water). A water footprint and EWP can be easily applied to the assessment of water savings of different crops in different locations, whilst crop water productivity can be used to compare crop cultivars of the same crops under different water management regimes. However, WF and CWP are both influenced by climate factors, crops or cultivars and water management.

The literature review has found few studies on economic water productivity relating to potato production. Consequently, strategies for maximising WUE in agriculture have not been accompanied by economic incentives. These strategies are based on physical output per volume of water used, rather than economic output per volume of water used for production. In view of this situation, the adoption of WUE strategies may encounter challenges, due to a lack of economic incentives. The review also indicates that crop cultivars with high efficiency in water use can improve generic and specific WUE, by enhancing the IWUE or ET-Yield slope, whilst efficient scheduling and an efficient irrigation system can improve WUE, by minimising water loss, that is, irrigation efficiency. It has also been reviewed that high NUE depends on an adequate amount of water, restricted N and cultivars, but it is currently challenged by the way in which agronomic, crop physiological features and genetic features can be combined, in order to achieve resource use efficiency, at plant and in the field.

Water use efficiency in potato depends on the plant’s water system called a Soil-Plant-Atmospheric Continuum, which varies with crop physiological and genetic features. The SPAC is controlled by stomatal and non-stomatal factors, in response to the atmosphere and soil environment. In turn, the atmospheric and soil environmental demands act as the regulatory components of potential crop evapotranspiration or crop water requirement (ETp), apart from the crop stomata. It has been reviewed that the potential ET for New Zealand is increasing with climate change. Irrigation water requirements will increase due to high anticipated potential ET for New Zealand. The consequence of increased ETp on agriculture has an economic water scarcity effect rather than a physical water scarcity effect, since it will increase the costs of production and environment management. This observation illustrates the significance of integrating both economic and physical water productivity appraisal in recommendations for future WUE strategies.

There are opportunities available to reduce the impact of economic water scarcity, through improved WUE (correct water and nutrient management, pest and disease management and selection of appropriate crop cultivars). The review has also shown that many studies have been undertaken on N and irrigation in modern potato in New Zealand and other countries, but combined studies on heritage and modern crop response to irrigation and N management have never been undertaken, despite its uniqueness. The effects of water, N and leaf canopy management practices, reported in other glasshouse and field studies worldwide, necessitated a full exploration (in the context of WUE in Taewa) at glasshouse and field level. There is evidence that efficient water, N management and HI improvement can increase Taewa production for small-scale farmers in New Zealand.

The generic and specific WUE information relating to Taewa and other heritage crops, such as oca and Kamokamo, is important for the majority of farmers, who are extending their crop diversification to other neglected vegetables, which can earn them more profits than seasonal vegetables. Physiological WUE, (based on photosynthetic capacity), tuber or fruit yield and WUE based on dollar value, together with quality properties (total and reduced sugar, specific gravity), for Taewa and modern potato, are required to be studied further, in order to support crop diversification within the New Zealand agricultural industry. Lack of information on physiological WUE and tuber yield for heritage cultivars, in comparison to modern crop cultivars, contributes to the wide gap of tuber yield between Taewa and modern potato cultivars. It is probable that the high yield and WUE reported in modern cultivars is a result of previous studies, which have led to improvement in management. Potato breeding has definitely increased tuber yield in modern potato. The high premium value of heritage cultivars, in relation to modern cultivars, also deserves further research for it to survive water scarcity (water costs increase and decline in water availability).

CHAPTER 3

COMPARISON OF WATER AND NITROGEN USE EFFICIENCY OF TAEWA AND MODERN POTATO CULTIVARS IN A GLASSHOUSE[2]

3.1 Introduction

Taewa or Maori potatoes are heritage potato cultivars, which have been used by Maori for 200 years (Roskruge, 1999). The supply of Taewa to its niche market in the cultural economy is generally restricted by low yields (Harris *et al.*, 1999; McFarlane, 2007). This is a consequence of insufficient scientific research and published agronomic work on Taewa. For example, there is scarce information available to Taewa growers on the benefits of irrigation and nitrogen management. This situation is in contrast to modern cultivars, which are typically produced on a large scale, mostly for domestic consumption either as table or processed potatoes.

There is substantial evidence that potato yields are influenced by water and soil nutrient availability and genotypes (Belanger *et al.,* 2002; Bowen, 2003). Taewa growers need to be able to manage inputs such as fertiliser and irrigation, in order to reduce water loss and N leaching that both reduce profits and also result in adverse environmental effects. The application of the concept of water and nitrogen use efficiency can help farmers optimise resource use and maximise profitability (Hoekstra *et al.,* 2007). A preliminary study was conducted on the performance of Taewa under modern production systems, with a focus on how they differ from modern cultivars in water and nitrogen use, at plant level. In the case of this preliminary study, a glasshouse offered a uniform environment for screening water and nutrient use traits (Sumanasena, 2003). The aim of the glasshouse experiment was to compare the physiological and morphological characteristics, in addition to water and nitrogen use efficiency in Taewa and modern potato cultivars, which were subjected to different levels of irrigation and nitrogen fertiliser.

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3.2 Material and Methods

3.2.1 Location and plant establishment

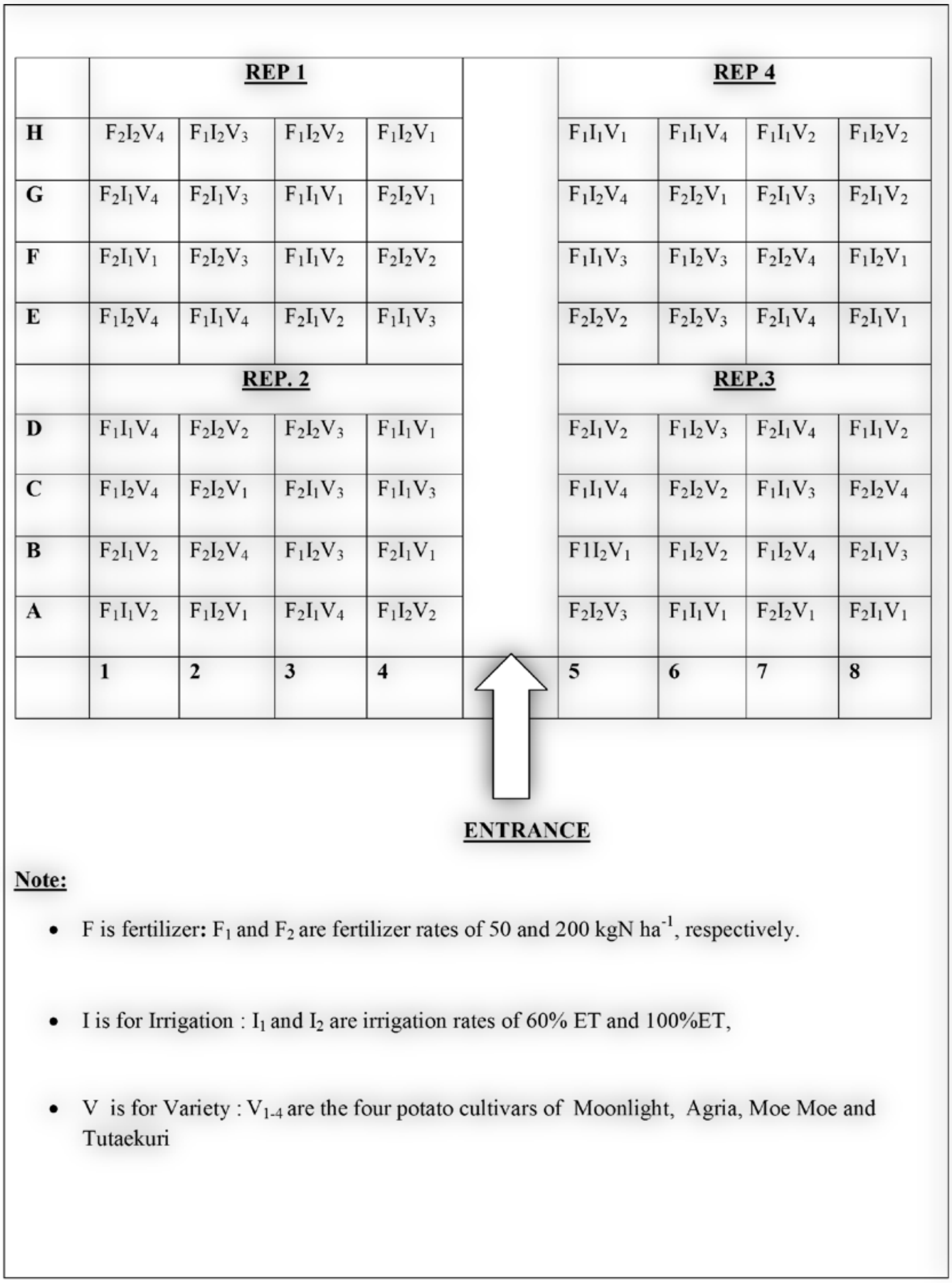
The experiment was located in a glasshouse at the Plant Growth Unit, Massey University, Palmerston North, from 23 June 2009 to 11 November 2009. Taewa cultivars, Moe Moe (*Solanum tuberosum ssp. tuberosum* L.) and Tutaekuri (*Solanum tuberosum ssp. andigena* Juz. & Buk.) and modern cultivars, Moonlight and Agria (*S. tuberosum ssp. tuberosum* L.) were planted on 23 June 2009. Taewa seed tubers were from Maori Resource Centre whilst modern potato seed tubers were obtained from a potato seed company, Morgan Laurenson Ltd. Seed tubers (one per bag) were planted in 15 **ℓ** plastic planting bags, which were partially filled with 10 **ℓ** of air-dried sieved (2 mm) soil: the soil type was Manawatu sandy loam, a recent alluvial soil. The soil properties were: pH 5.4, Olsen P 36 mg kg^{-1}, available nitrogen (N) 76.81 mg kg^{-1} and K 86.02 mg kg^{-1}. The soil bulk density was 1.35 g cm^{-3} and the volumetric soil water content, at field capacity and wilting point, were 0.35 and 0.17 m^3 m^{-3}, respectively. The planting bags were arranged in a square grid pattern spaced at 70 cm (Fig.3.1). The glasshouse temperature was regulated between 15°C and 25°C for the entire period.

3.2.2 Treatments and experimental design

The experiment was laid out as a 2 * 2 * 4 factorial experimental design with four replicates (two water regimes, * two N rates, * four potato cultivars). In addition, eight bags were planted with *Brassica napus L.* (two per replicate) which was selected as a reference crop, due to its high potential water use for monitoring actual evapotranspiration (Wright *et al.*, 1995).

3.2.2.1 Irrigation and nitrogen fertiliser treatments

Irrigation treatments were based on reference crop evapotranspiration (ETo), implemented by applying 60 ET% (I_1) and 100% ET (I_2) every four days, up to day 77 after planting and subsequently, every two days. Irrigation to replenish the planting bags to field capacity was determined by weighing the *B. napus L* reference bag before and after irrigation, to obtain the mean ETo within the irrigation interval. The two N fertiliser application rates were 0.70 g N bag^{-1} or (50 kg N ha^{-1}) and 2.8 g N bag^{-1} or (200 kg N ha^{-1}) as urea. Urea was diluted to a concentration of 14 gl^{-1} in water and applied manually in split application as basal dressing and top dressing.



	REP 1					**REP 4**			
H	$F_2I_2V_4$	$F_1I_2V_3$	$F_1I_2V_2$	$F_1I_2V_1$		$F_1I_1V_1$	$F_1I_1V_4$	$F_1I_1V_2$	$F_1I_2V_2$
G	$F_2I_1V_4$	$F_2I_1V_3$	$F_1I_1V_1$	$F_2I_2V_1$		$F_1I_2V_4$	$F_2I_2V_1$	$F_2I_1V_3$	$F_2I_1V_2$
F	$F_2I_1V_1$	$F_2I_2V_3$	$F_1I_1V_2$	$F_2I_2V_2$		$F_1I_1V_3$	$F_1I_2V_3$	$F_2I_2V_4$	$F_1I_2V_1$
E	$F_1I_2V_4$	$F_1I_1V_4$	$F_2I_1V_2$	$F_1I_1V_3$		$F_2I_2V_2$	$F_2I_2V_3$	$F_2I_1V_4$	$F_2I_1V_1$
	REP. 2					**REP.3**			
D	$F_1I_1V_4$	$F_2I_2V_2$	$F_2I_2V_3$	$F_1I_1V_1$		$F_2I_1V_2$	$F_1I_2V_3$	$F_2I_1V_4$	$F_1I_1V_2$
C	$F_1I_2V_4$	$F_2I_2V_1$	$F_2I_1V_3$	$F_1I_1V_3$		$F_1I_1V_4$	$F_2I_2V_2$	$F_1I_1V_3$	$F_2I_2V_4$
B	$F_2I_1V_2$	$F_2I_2V_4$	$F_1I_2V_3$	$F_2I_1V_1$		$F1I_2V_1$	$F_1I_2V_2$	$F_1I_2V_4$	$F_2I_1V_3$
A	$F_1I_1V_2$	$F_1I_2V_1$	$F_2I_1V_4$	$F_1I_2V_2$		$F_2I_2V_3$	$F_1I_1V_1$	$F_2I_2V_1$	$F_2I_1V_1$
	1	**2**	**3**	**4**		**5**	**6**	**7**	**8**

ENTRANCE

Note:

- F is fertilizer**:** F_1 and F_2 are fertilizer rates of 50 and 200 kgN ha^{-1}, respectively.
- I is for Irrigation : I_1 and I_2 are irrigation rates of 60% ET and 100%ET,
- V is for Variety : $V_{1\text{-}4}$ are the four potato cultivars of Moonlight, Agria, Moe Moe and Tutaekuri

Figure 3.8 Layout of planting bags in the glasshouse

3.2.2.2 Plant protection

All potato plants in the glasshouse were sprayed fortnightly, by hand, with TARATEK 5F fungicides (250 g litre^{-1} chlorothalonil and 250 g litre^{-1} thi-ophanate methyl), in order to control late blight. CHESS^{R} WG (500 g kg^{-1} pymetrozine) and ORTHENE WSG (970 g litre^{-1} acephate) insecticides were applied to control potato aphids (*Macrosiphum euphorbiae* Thomas), whitefly (*Bemisia argentifolii* Bellows & Perring) and Solanum psyllid (*Bactericera cockerelli* Sulc). A number of Tutaekuri plants displayed symptoms (leaf curling and yellowing) of potato leaf roll virus infection (Roskruge 2009 Pers. Com.). Consequently, all the Tutaekuri plants were scored for severity of symptoms, on a scale of 0-5 (Table 3.1).

3.2.3 Crop physiological and soil moisture measurements

3.2.3.1 Vegetative growth characteristics

Vegetative growth characteristics, recorded on the 100th day after planting, were the number of stems per plant; plant height; stem diameter; number of compound leaves per plant; viral foliar diseases; canopy cover (%); leaf area index (LAI); and specific leaf area (SLA). Leaf area was measured using a leaf area meter (Model 3100 Area Meter) and LAI was calculated as the total leaf surface area per unit ground area. After oven drying and weighing the leaf samples, the SLA (cm^{2} g^{-1}) was determined as a measure of leaf thickness, by dividing leaf area per plant by leaf dry weight per plant (Amanullah *et al.,* 2007; Vile *et al.,* 2005). Leaf dry matter content (g g^{-1}) was determined by dividing leaf dry weight per plant by leaf fresh weight per plant (Vile *et al.,* 2005). Leaf canopy (being the spatial arrangement of the above-ground organs) was determined using $K_{cp}1$ equation for plant coverage: $Kcp1 = \frac{Wp}{Wb} * 100$, (Ertek *et al.*, 2006), where W_p is the plant canopy width (cm) and W_b is the pot spacing (cm).

3.2.3.2 Photosynthetic water use efficiency and gaseous exchange

Photosynthetic water use efficiency (μmol CO_2/mmol H_2O), defined as how efficiently the potato plant obtained carbon dioxide for photosynthesis, with a given amount of water, was determined as the ratio of net photosynthesis (A_n) to transpiration rate (T) (Xu & Hsiao, 2004; Liu *et al.*, 2006a). CIRAS-2, a portable photosynthesis system (V2.01), was used to measure A_n (μmolCO_2 m^{2} s^{-1}); T (m molH_2O m^{2} s^{-1}); leaf stomata conductance (m molCO_2 m^2 s^{-1}); internal CO_2 concentration (ppm); and leaf vapour pressure deficit (bars), between 1000 - 1200 hrs, on newly expanded leaves (3rd leaf on main axis). Photosynthetic active radiation (µmol photons m^2 s^{-1}) and reference CO_2 (ppm) were respectively maintained at an average of 1400 and 400, during all the CIRAS measurements. Measurements took 1-2 minutes per plant. Gaseous exchange was measured four times, between 20 and 90 days after plant emergence (DAE).

3.2.3.3 Soil moisture content

9.5 ℓ of water was applied uniformly in each planting bag, for both irrigation treatments, up to day 50 from planting (Fig. 3.2). Irrigation scheduling, which was later based on the reference crop, *Brassica napus*, determined the remainder, in order to obtain the total cumulative evapotranspiration for the treatments, from planting to harvesting (Fig.3.2). The volumetric soil moisture content in the bags was measured weekly, using a time-domain reflectometer (TDR, model 1502C, Tektronix Inc., Beaverton, OR, USA).

3.2.4 Tuber yield, water and nitrogen use efficiency

Harvesting was undertaken once, after physiological maturity on 11th November, 2010. The number of tubers per plant, individual tuber weight (g) and total tuber weight (g), were measured. Water use efficiency (WUE) was determined as the total tuber yield (g), per unit of water used (ℓ bag^{-1}). Nitrogen use efficiency (NUE) was determined as the total tuber yield (g), per unit of N applied per bag (g N bag^{-1}) (Darwish *et al.*, 2006).

3.2.5 Specific gravity and tuber dry matter content

After harvesting, ten potato tubers were randomly selected from each planter bag, to be used for tuber dry matter content (DM) and specific gravity (SG) determination (Plate 3.1). The samples were thoroughly washed and dried before weighing. The expression of SG was determined by weighing the potato in air and in water (Haase, 2003; Smith, 1975), using Mettler PJ3600 Delta Range scale, to two decimal places (Plate 3.1). The specific gravity was calculated using the following equation:

$$\text{Specific gravity} = \frac{\text{Weight of tuber in Air}}{(\text{Weight of tuber in Air} - \text{Weight in water})} \quad \text{Equation 3.1}$$

The DM was determined by oven drying chopped potato at 70 ^{o}C, until the change in DM was constant, which was soon after determining its SG. The initial and final weight, for each sample, was measured and the DM% was calculated, by dividing the final dry weight by the initial fresh weight and then multiplying it by 100. Additionally, DM% and starch (%) were predicted, using regression models (Haase, 2003).

3.2.6 Statistical analysis

The data on soil moisture, physiological and morphological characteristics, tuber yield and yield components measurements and water and nitrogen use efficiency, were analysed with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS) (SAS, 2008) and differences amongst treatment means were compared by the Least Significant Difference test (LSD) at 5% probability (Meier, 2006). Pearson correlation analysis was used to determine the relationship between tuber yield and crop water use and photosynthetic WUE and gaseous exchange parameters.

Description: Large bucket was filled with water and small bucket with potato. Small bucket was tied with chain hanged on scale. Small bucket containing potato was being floated in large bucket to determine specific gravity.

Moe Moe

Tutaekuri

Agria

Moonlight

Plate 3.1 Measurement for specific gravity and sample of Moe Moe, Tutaekuri, Moonlight and Agria tubers

3.3 Results

3.3.1 Evapotranspiration and soil moisture content (%)

3.3.1.1 Cumulative evapotranspiration from planting

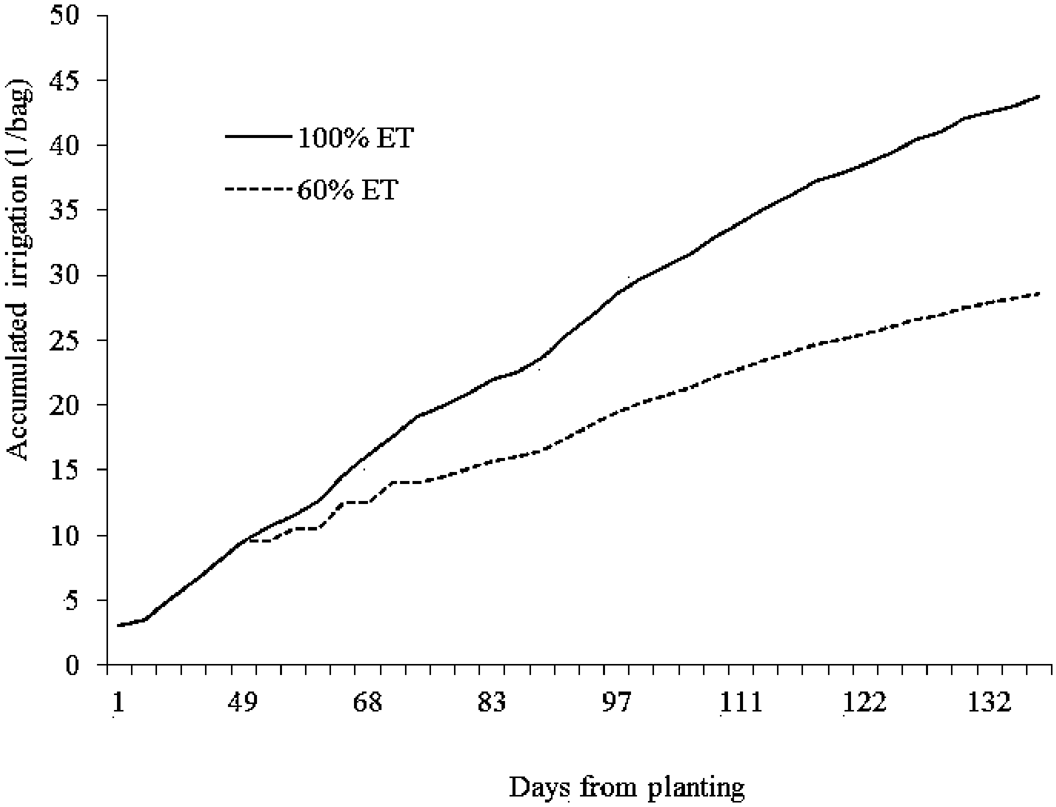


Figure 3.9 Total irrigation accumulated after planting in the glasshouse

Total cumulative evapotranspiration was 28.6 ℓ and 43.7 ℓ for the 60% ET and 100% ET irrigation treatments, respectively (Fig. 3.2). The cumulative irrigation (ℓ /bag) increased throughout the growing period. The trend portrayed by the reference crop enabled adjustments to keep the experimental crop well watered, throughout the experimentation period (Fig. 3.2).

3.3.1.2 Volumetric soil water content (%)

Volumetric soil moisture content was strongly influenced by cultivar ($P<0.05$), irrigation ($P<0.0001$), and N ($P<0.0001$), between 20 and 85 days after planting. Cultivars and the irrigation regime differences were observed from days 20 to 85, whilst the N regime had a significant effect between days 71 and 85 ($P<0.0001$, $P<0.05$) (Fig. 3.3, Appendix 3.1). Interactions between cultivars and irrigation ($P<0.01$) were recorded for days 57 to 71.

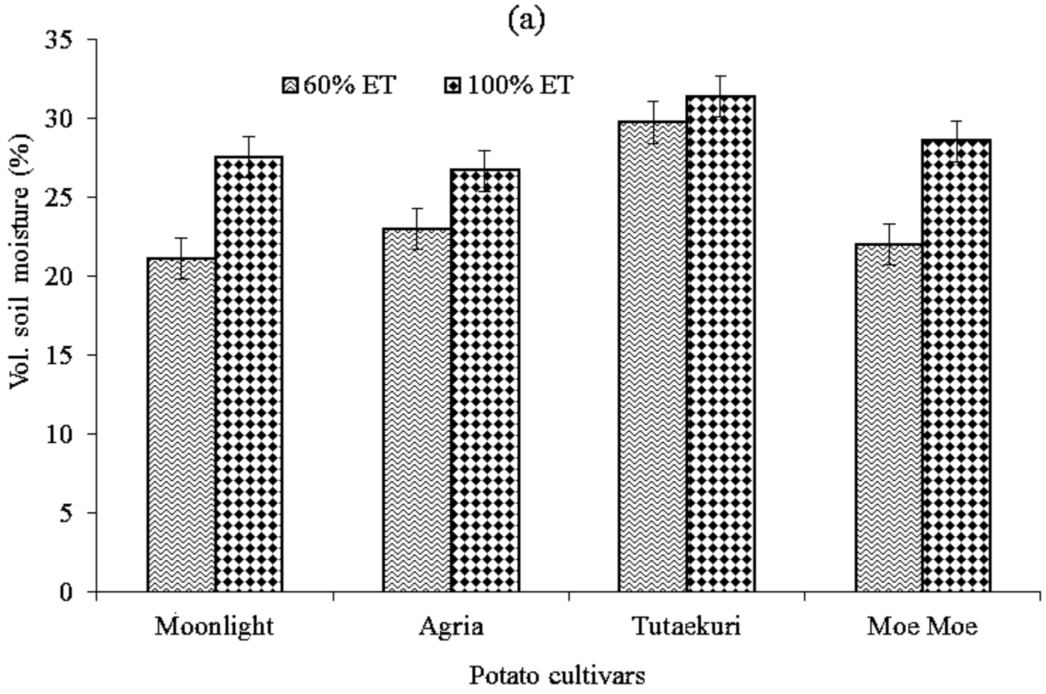


Figure 3.3 (a) Interaction between irrigation and cultivar on volumetric soil moisture content (%) during the experiment period. Error bar represents LSD at 5%.

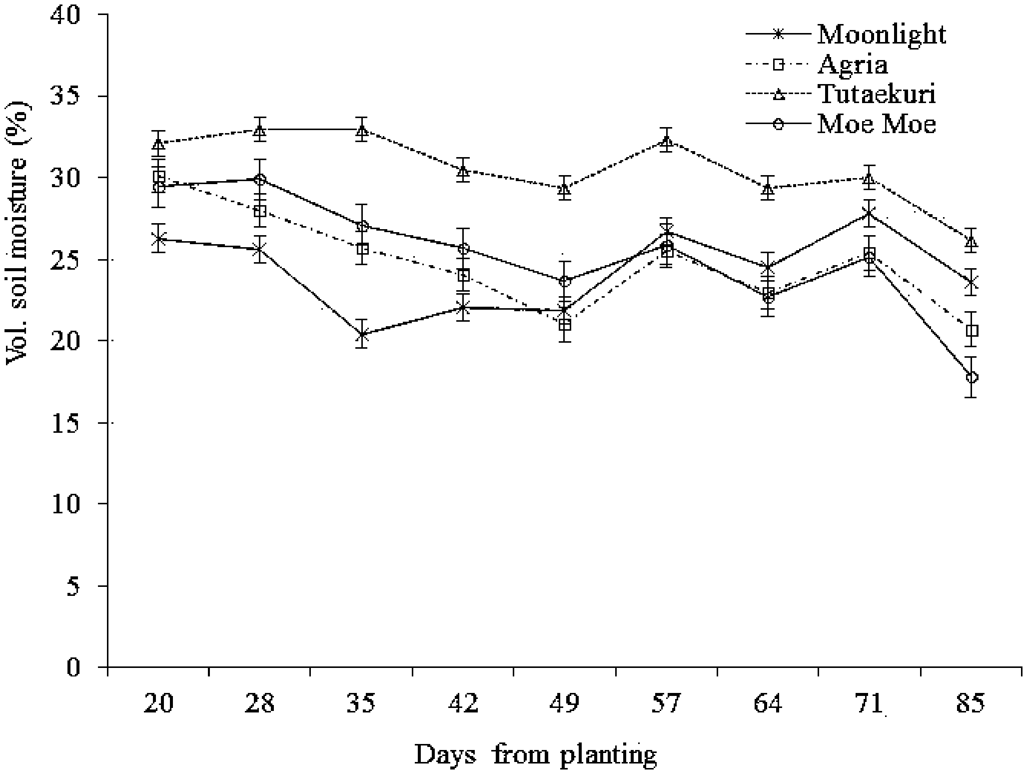


Figure 3.10 (b) Change in volumetric soil moisture content (%) for each cultivar over time. Error bar represents LSD at 5%.

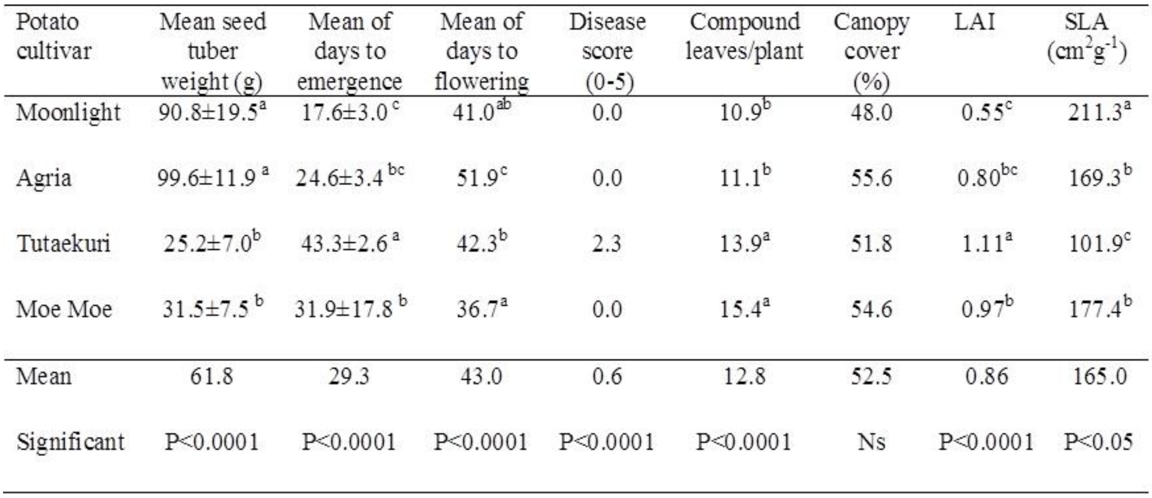
The interaction was a result of an increase in water extraction by Moe Moe, whereas Moonlight and Agria decreased water extraction, compared to Moe Moe within this period (Fig. 3.3b). Plant water extraction from the soil increased with plant growth (Fig. 3.3). 100% ET had higher volumetric soil content than 60% ET (Fig. 3.3a). Amongst the four cultivars, Tutaekuri extracted the least water, from day 20 to 85, whilst the remaining cultivars did not differ in soil moisture content (P>0.05) (Appendix 3.1).

3.3.2 Vegetative growth characteristics in four potato cultivars

3.3.2.1 Potato seed size, days after emergence (DAE) and flowering production

The average tuber weight of the seed potatoes at planting was significantly different, with a range from 25.20±7.01 (g) to 99.58±11.97 (g) (P<0.0001, Table 3.1). The modern cultivars, Agria and Moonlight, had a larger seed tuber than Tutaekuri and Moe Moe. Days to emergence differed amongst the cultivars (P<0.0001). Moonlight, followed by Agria, was the earliest cultivar to emerge, whilst the Taewa cultivars, Tutaekuri and Moe Moe, were the last to emerge.

Table 3.1 Mean potato seed tuber weight (g), days to emergence, flowering, disease scores at 0 - 5 scale and leaf features.



Potato cultivar	Mean seed tuber weight (g)	Mean of days to emergence	Mean of days to flowering	Disease score (0-5)	Compound leaves/plant	Canopy cover (%)	LAI	SLA (cm^2g^{-1})
Moonlight	90.8±19.5^{a}	17.6±3.0^{c}	41.0^{ab}	0.0	10.9^{b}	48.0	0.55^{c}	211.3^{a}
Agria	99.6±11.9^{a}	24.6±3.4^{bc}	51.9^{c}	0.0	11.1^{b}	55.6	0.80^{bc}	169.3^{b}
Tutaekuri	25.2±7.0^{b}	43.3±2.6^{a}	42.3^{b}	2.3	13.9^{a}	51.8	1.11^{a}	101.9^{c}
Moe Moe	31.5±7.5^{b}	31.9±17.8^{b}	36.7^{a}	0.0	15.4^{a}	54.6	0.97^{b}	177.4^{b}
Mean	61.8	29.3	43.0	0.6	12.8	52.5	0.86	165.0
Significant	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	Ns	P<0.0001	P<0.05

Note: Column rows with same letters are not significantly different, LAI is average leaf area index and SLA is specific leaf area at physiological maturity.

3.3.2.2 Flower production and physiological maturity

Days from date of emergence, to date of 50% flowering, differed between potato cultivars ($P<0.0001$; Table 3.1). Moe Moe had the shortest duration to flowering: it flowered 37 days after emergence, whilst the last to flower, Agria, flowered after 52 days (Table 3.1). Days to flowering in all cultivars were not affected by irrigation and N ($P>0.05$). All four cultivars were harvested on 11th November 2010, 141 days from planting.

3.3.2.3 Average number of stems per plant

Moonlight had the greatest number of stems per plant, followed by Agria: Agria was not different to Moe Moe, but it was greater than Tutaekuri ($P<0.0001$, Table 3.2). Irrigation and N had no effect on the number of stems per plant ($P>0.05$). The number of stems per plant were affected by an irrigation*N interaction ($P<0.05$) and an irrigation*N*cultivar interaction ($P<0.05$), in addition to a cultivar*irrigation interaction ($P<0.05$, Table 3.2). The interaction effects were not consistent in all the cultivars. Irrigation and N increased stem number per plant, in Agria and Moe Moe, but it reduced stem numbers in Moonlight and Tutaekuri (Table 3.2).

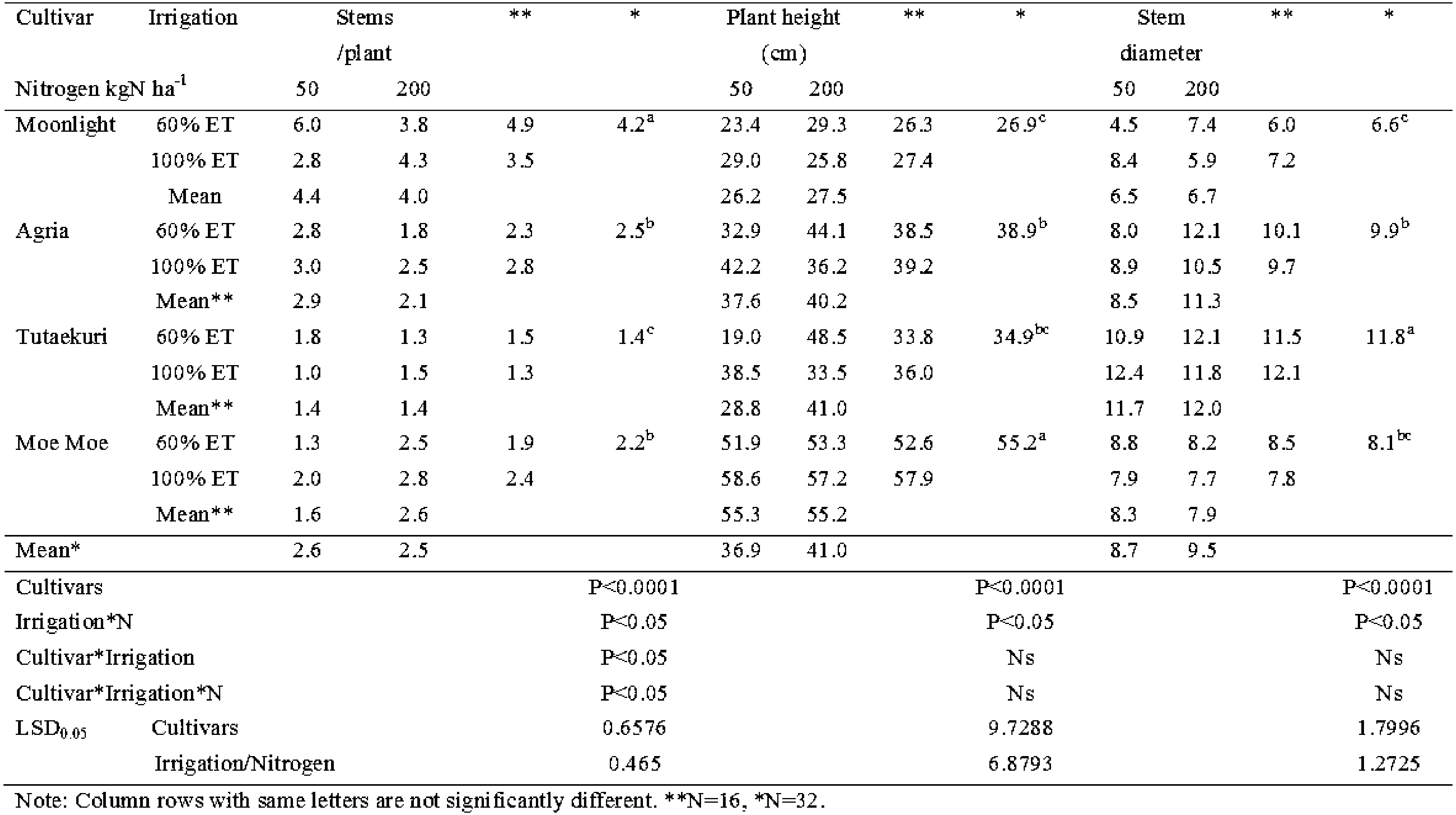
3.3.2.4 Average plant height (cm)

Moe Moe was the tallest cultivar, whilst Moonlight was the shortest cultivar ($P<0.0001$, Table 3.2). The plant heights for Agria and Tutaekuri were not different from each other. Irrigation and N had no effect on plant height, but there was interaction between N and irrigation ($P<0.05$). This interaction was caused by an increase in plant height under 60% ET with N increase and a plant height decrease with N increase under 100% ET.

3.3.2.5 Average stem diameter (mm)

Tutaekuri had the largest stem diameter, whilst Moonlight had the smallest stem diameter ($P<0.0001$, Table 3.2). The stem diameter for Agria and Moe Moe were not significantly different ($P>0.05$). There was a significant irrigation and N regime interaction on plant stem diameter ($P<0.05$) caused by an increase in stem diameter under 60% ET with N increase, whilst it decreased with N increase under 100% ET.

Table 3.2 Potato characteristics on number of stems per plant, plant height (cm) and stem diameter (mm) in the glasshouse, 2009



Cultivar	Irrigation	Stems /plant		**	*	Plant height (cm)		**	*	Stem diameter		**	*
Nitrogen kgN ha^{-1}		50	200			50	200			50	200		
Moonlight	60% ET	6.0	3.8	4.9	4.2^{a}	23.4	29.3	26.3	26.9^{c}	4.5	7.4	6.0	6.6^{c}
	100% ET	2.8	4.3	3.5		29.0	25.8	27.4		8.4	5.9	7.2	
	Mean	4.4	4.0			26.2	27.5			6.5	6.7		
Agria	60% ET	2.8	1.8	2.3	2.5^{b}	32.9	44.1	38.5	38.9^{b}	8.0	12.1	10.1	9.9^{b}
	100% ET	3.0	2.5	2.8		42.2	36.2	39.2		8.9	10.5	9.7	
	Mean**	2.9	2.1			37.6	40.2			8.5	11.3		
Tutaekuri	60% ET	1.8	1.3	1.5	1.4^{c}	19.0	48.5	33.8	34.9^{bc}	10.9	12.1	11.5	11.8^{a}
	100% ET	1.0	1.5	1.3		38.5	33.5	36.0		12.4	11.8	12.1	
	Mean**	1.4	1.4			28.8	41.0			11.7	12.0		
Moe Moe	60% ET	1.3	2.5	1.9	2.2^{b}	51.9	53.3	52.6	55.2^{a}	8.8	8.2	8.5	8.1^{bc}
	100% ET	2.0	2.8	2.4		58.6	57.2	57.9		7.9	7.7	7.8	
	Mean**	1.6	2.6			55.3	55.2			8.3	7.9		
Mean*		2.6	2.5			36.9	41.0			8.7	9.5		
Cultivars					$P<0.0001$				$P<0.0001$				$P<0.0001$
Irrigation*N					$P<0.05$				$P<0.05$				$P<0.05$
Cultivar*Irrigation					$P<0.05$				Ns				Ns
Cultivar*Irrigation*N					$P<0.05$				Ns				Ns
$LSD_{0.05}$	Cultivars				0.6576				9.7288				1.7996
	Irrigation/Nitrogen				0.465				6.8793				1.2725

Note: Column rows with same letters are not significantly different. **N=16, *N=32.

3.3.2.6 Leaf morphological characteristics and diseases

Moe Moe had high leaf numbers per plant: significantly greater than Moonlight and Agria ($P<0.0001$) (Table 3.1). Plant canopy (%) was not affected by cultivars. Tutaekuri had a higher LAI than the other cultivars ($P<0.0001$). Moonlight had a higher SLA than all the other cultivars ($P<0.05$). Tutaekuri was significantly affected by potato leaf-roll virus (characterised by the rolling of leaves, leaf curling, yellowing and stunted growth), whilst none of the other cultivars displayed any symptoms ($P<0.0001$).

3.3.3 Photosynthetic water use efficiency and gaseous exchange in the glasshouse

3.3.3.1 Photosynthetic water use efficiency (µmol CO_2/mmol H_2O) in four potato cultivars

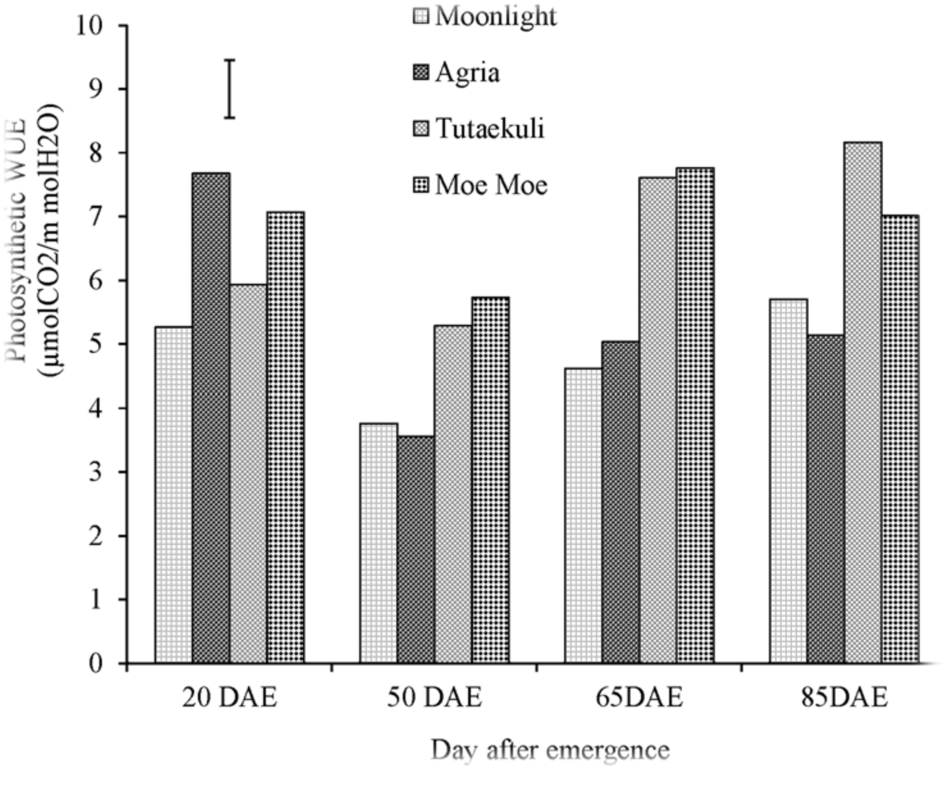


Figure 3. 11 Photosynthetic WUE for different potato cultivars*DAE. Error bar represents ±SEM.

Photosynthetic WUE (µmol CO_2/mmol H_2O) was significantly influenced by potato cultivar ($P<0.0001$) and DAE ($P<0.01$) (Table 3.3). On average, Moe Moe and Tutaekuri had the highest photosynthetic WUE. Mean photosynthetic WUE was lowest on day 50 and highest on day 20, although there was no statistical difference between days 65 and 85 (Table 3.3, Fig.3.4).

3.3.3.2 Net photosynthesis (µmolCO$_2$ m^2 s^{-1}) of four potato cultivars

Net photosynthesis (A_n) significantly differed between cultivars ($P<0.0001$), irrigation ($P<0.0001$), N regimes ($P<0.0001$) and DAE ($P<0.0001$, Table 3.3, Appendix 3.2). Taewa (particularly Moe Moe) had the highest average A_n throughout the growing period, except for day 20, when Agria had the highest average A_n (Appendix 3.2). Net photosynthesis tended to decrease from day 20 to 85 ($P>0.0001$, Table 3.3). On average, A_n was highest on day 20, except in Moe Moe, which was highest on both day 20 and 50 (Appendix 3.2). There was an interaction between DAE*cultivars ($P<0.001$, Appendix 3.2) and potato cultivar*irrigation*N ($P<0.05$) for A_n. High irrigation and high N increased A_n in modern cultivars, whilst it decreased it in Taewa, with the largest reduction being in Tutaekuri (Fig.3.5; Appendix 3.2a).

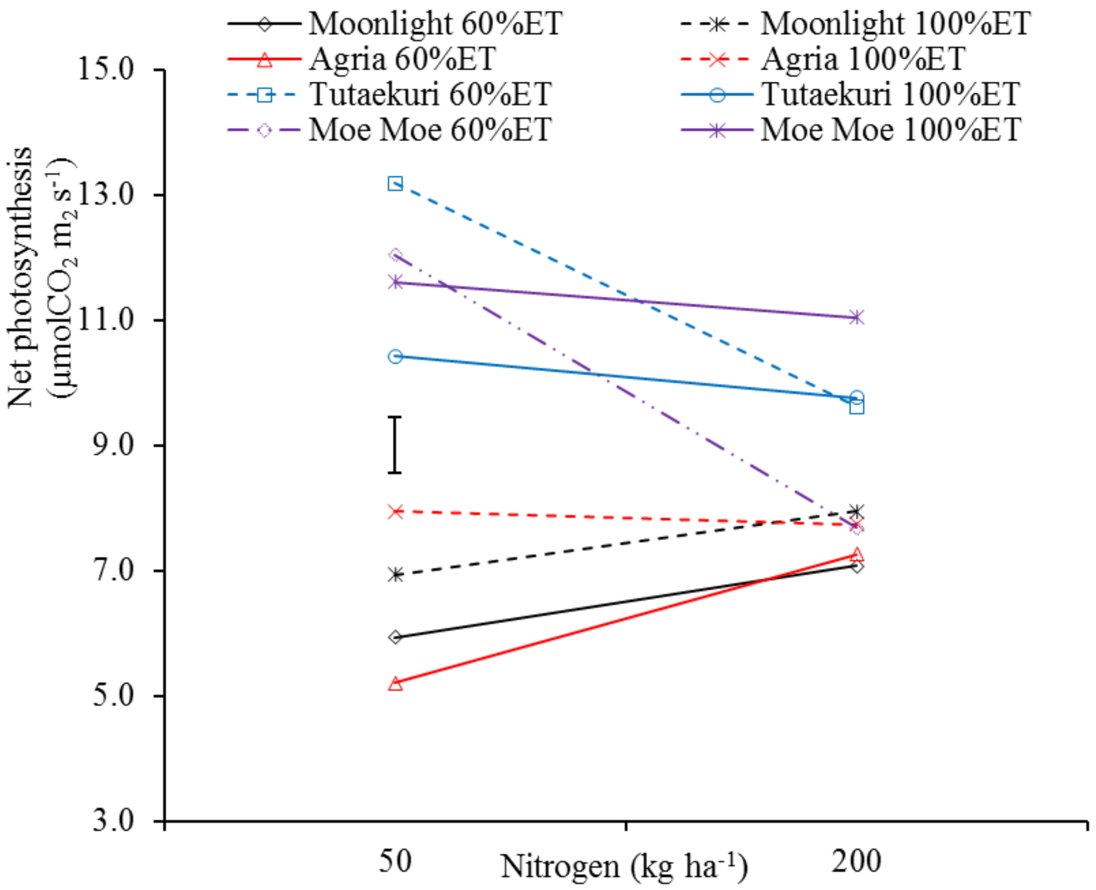


Figure 3. 12 Interaction between irrigation, nitrogen and potato cultivars on A_n in the glasshouse, 2009. Error bar represents ±SEM.

3.3.3.3 Stomatal conductance (m molCO2 m2 s-1) of four potato cultivars

Stomatal conductance (g_s), significantly differed with cultivar ($P<0.05$), N ($P<0.01$) and DAE ($P<0.0001$, Table 3.3). The g_s significantly increased up to day 65 and then decreased, under both irrigation and N treatments (Appendix 3.2b). Nitrogen enhanced g_s whilst irrigation influence was observed on day 50 ($P<0.05$). In most cases, the modern cultivar, Agria, had the highest gs, whilst the Taewa (particularly Moe Moe), had the lowest g_s.

3.3.3.4 Transpiration rate (m molH2O m2 s-1) of four potato cultivar

Transpiration rates (T) were influenced by cultivar ($P<0.05$) and DAE ($P<0.0001$, Table 3.3). Agria had the greatest T, whilst Moe Moe had the lowest T. The maximum T, for almost all cultivars, was on day 50, when irrigation had a significant effect on T and the lowest T was on day 85 ($P<0.05$). The general trend was that the cultivar with the highest g_s also had the highest T and lower A_n.

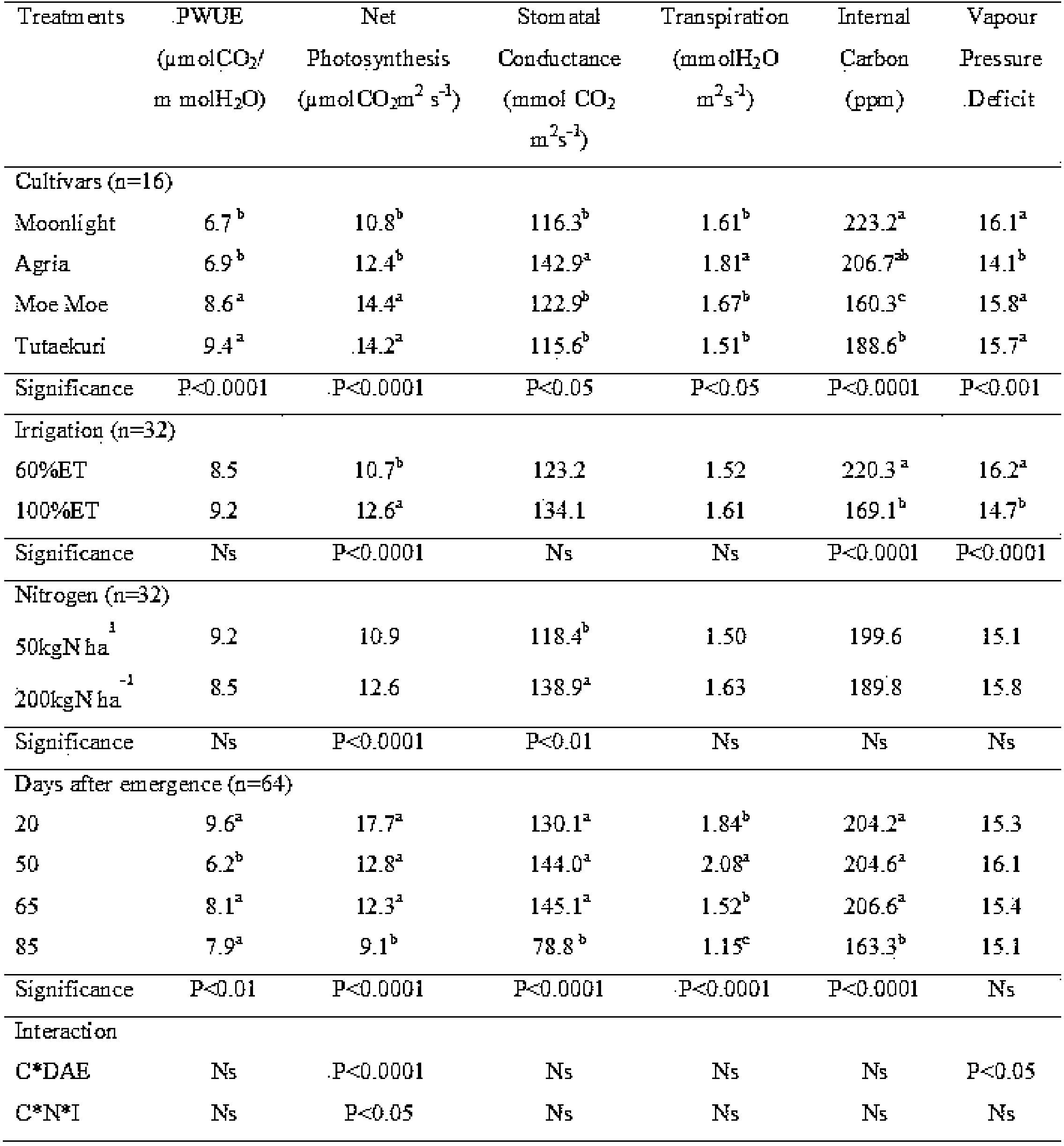
3.3.3.5 Internal CO_2 concentration (Ci) and vapour pressure deficits (VPD)

Moonlight and Agria had the greatest Ci, whilst Taewa had the lowest Ci ($P<0.0001$, Table 3.3). Vapour pressure deficit was high in Moonlight, although it was not different from Tutaekuri and Moe Moe, but it was higher than Agria, which was lowest in VPD ($P<0.001$). Irrigation significantly reduced leaf VPD and Ci ($P<0.0001$), whilst N did not affect VPD or Ci ($P<0.0001$) (Table 3.3).

3.3.3.6: The relationship of photosynthetic WUE to gaseous exchange variables

The relationship between photosynthetic WUE and other gaseous exchange variables was explored, by using simple correlation (Table 3.4). With all the data combined, there was a correlation between photosynthetic WUE and T ($r = 0.58$, $P<0.0001$); g_s ($r = -0.45$, $P<0.0001$); leaf temperature ($r = -0.46$, $P<0.0001$); A_n ($r = 0.35$, $P<0.0001$); Ci ($r = -0.45$, $P<0.0001$) and VPD ($r = -0.012$, $P>0.05$). When data were stratified by cultivars, a moderately strong negative ($P<0.0001$) correlation was identified with T, leaf temperature, gs and Ci, in all cultivars. The correlation between Ci and T was very strong in the modern cultivars, compared to Moe Moe (Table 3.4).

Table 3.3 Photosynthetic WUE (PWUE) and gaseous exchange in four potato cultivars in the glasshouse, 2009



Treatments	PWUE (μmolCO$_2$/ m molH$_2$O)	Net Photosynthesis (μmolCO$_2$m^{2} s^{-1})	Stomatal Conductance (mmol CO$_2$ m^{2}s^{-1})	Transpiration (mmolH$_2$O m^{2}s^{-1})	Internal Carbon (ppm)	Vapour Pressure Deficit
Cultivars (n=16)						
Moonlight	6.7^{b}	10.8^{b}	116.3^{b}	1.61^{b}	223.2^{a}	16.1^{a}
Agria	6.9^{b}	12.4^{b}	142.9^{a}	1.81^{a}	206.7^{ab}	14.1^{b}
Moe Moe	8.6^{a}	14.4^{a}	122.9^{b}	1.67^{b}	160.3^{c}	15.8^{a}
Tutaekuri	9.4^{a}	14.2^{a}	115.6^{b}	1.51^{b}	188.6^{b}	15.7^{a}
Significance	P<0.0001	P<0.0001	P<0.05	P<0.05	P<0.0001	P<0.001
Irrigation (n=32)						
60%ET	8.5	10.7^{b}	123.2	1.52	220.3^{a}	16.2^{a}
100%ET	9.2	12.6^{a}	134.1	1.61	169.1^{b}	14.7^{b}
Significance	Ns	P<0.0001	Ns	Ns	P<0.0001	P<0.0001
Nitrogen (n=32)						
50kgN ha^{1}	9.2	10.9	118.4^{b}	1.50	199.6	15.1
200kgN ha^{-1}	8.5	12.6	138.9^{a}	1.63	189.8	15.8
Significance	Ns	P<0.0001	P<0.01	Ns	Ns	Ns
Days after emergence (n=64)						
20	9.6^{a}	17.7^{a}	130.1^{a}	1.84^{b}	204.2^{a}	15.3
50	6.2^{b}	12.8^{a}	144.0^{a}	2.08^{a}	204.6^{a}	16.1
65	8.1^{a}	12.3^{a}	145.1^{a}	1.52^{b}	206.6^{a}	15.4
85	7.9^{a}	9.1^{b}	78.8^{b}	1.15^{c}	163.3^{b}	15.1
Significance	P<0.01	P<0.0001	P<0.0001	P<0.0001	P<0.0001	Ns
Interaction						
C*DAE	Ns	P<0.0001	Ns	Ns	Ns	P<0.05
C*N*I	Ns	P<0.05	Ns	Ns	Ns	Ns

Note: Column rows with same letters are not significantly different, C = cultivar, N=nitrogen, I=irrigation, DAE = day after emergence.

When stratified by irrigation, photosynthetic WUE was strongly correlated ($P<0.0001$) to T, g_s, leaf temperature, A_n, Ci; 60ET% (r = - 0.52, r = - 0.42, r = - 0.35, r = 0.31, r = 0.31, r = - 0.02); and 100% ET (r = - 0.68, - 0.58, - 0.58, 0.039, - 0.66), respectively. Data stratified by N analysis revealed a correlation between photosynthetic WUE and T, g_s, leaf temperature, A_n, Ci; low N ($P<0.0001$) (r = - 0.62, - 0.53, - 0.48, 0.31, - 0.28, 0.05) and high N ($P<0.0001$), (r = - 0.52, - 0.41, - 0.41, 0.45, - 0.72), respectively. There were no correlations between photosynthetic WUE and VPD.

Table 3.4 Photosynthetic WUE relationship with A_n, T and g_s, leaf temperature (LT), Ci, leaf VPD in four potato cultivars

Cultivars	PWUE*T	PWUE* A_n	PWUE*g_s	PWUE*Ci	PWUE*LT	PWUE*VPD
Moonlight	r = -0.60,	r = 0.57	r = -.045	r = -0.77	r = -0.31	r = 0.04
	P<0.0001	P<0.0001	P<0.001	P<0.0001	P<0.05	P>0.05
Agria	r =-0.78	r = 0.28	r = -0.64	r = -0.57	r = -0.38	r = 0.00
	P<0.0001	P>0.05	P<0.0001	P>0.0001	P<0.05	P>0.05
Moe Moe	r = -0.38	r = 0.20	r = -0.26	r = -0.27	r = -0.17	r = -0.09
	P<0.01	P>0.05	P<0.05	P<0.05	P>0.05	P>0.05
Tutaekuri	r = -0.73	r = 0.17	r = -0.58	r = -0.30	r = 0.12	r = -0.3
	P<0.0001	P>0.05	P<0.0001	P<0.05	P>0.05	P>0.05

Note: A_n = net photosynthesis; T = transpiration rate; g_s = stomatal conductance; VPD = leaf vapour pressure deficit; Ci = internal carbon concentration and PWUE = photosynthetic water use efficiency

3.3.4. Tuber yield response to irrigation and N regime in four potato cultivars

The number of tubers per plant, mean tuber weight and total tuber weight were strongly affected by cultivar (P<0.0001, Table 3.5). Irrigation (P<0.0001) and N (P<0.01) increased the total tuber yield per plant, but it did not influence the number of tubers per plant and mean tuber weight. Increased irrigation, from 60% ET to 100% ET, increased the total tuber yield per plant in all the cultivars. Tuber yields were increased by 35%, 30%, 57% and 41%, for Moonlight, Agria, Tutaekuri and Moe Moe, respectively. Similarly, N also increased total tuber yield per plant in Moonlight, Agria, Tutaekuri and Moe Moe, by 16%, 10%, 8% and 10%, respectively. Nitrogen responses in low irrigation were generally less than those for high irrigation (Table 3.5).

There were significant interactions between cultivar and irrigation treatments on the number of tubers per plant (P<0.01) and mean tuber weight (P<0.01) (Table 3.5 and Fig. 3.6). Significant interactions were also observed between cultivar, irrigation and N, on tuber numbers per plant (P<0.05) and total tuber weight per plant (P<0.01) (Fig. 3.6). The interaction involving tuber yield resulted from the decrease in yield, at the high N and 100% ET irrigation in Tutaekuri, whereas in the other cultivars high N and 100% ET did not reduce yield. In contrast, high N increased yield at 60% ET while decreasing at 100% ET in Tutaekuri (Fig. 3.6). The mean tuber weight and total tuber yield per plant, in Agria, were higher than all the other cultivars, whilst Moe Moe had the highest number of tubers per plant.

Table 3.5 Yield response to irrigation and nitrogen regime in four potato cultivars under glasshouse conditions.

Cultivar	Irrigation	Tubers per Plant				Mean Tuber Weight(g)				Tuber Yield (g/bag)			
Nitrogen (Kg N/ ha)		50	200			50	200			50	200		
Moonlight				(**)	(*)			(**)	(*)			(**)	(*)
	60% ET	13.0	12.8	12.9	11.1^{b}	25.8	31.3	28.5^{bc}	44.3^{b}	320.8	360.3	340.5^{b}	399.3^{b}
	100% ET	7.0	11.8	9.4		72.4	47.5	60.0^{a}		419.5	496.8	458.1^{a}	
	(**)	10.0	12.3			49.1	39.4			370.1^{b}	428.5^{a}		
Agria													
	60% ET	7.5	6.0	6.8	7.1^{c}	59.5	75.2	67.4^{a}	70.0^{a}	396.3	410.5	403.4^{b}	464.5^{a}
	100% ET	7.0	8.0	7.5		73.6	71.5	72.6^{a}		486.8	564.5	525.6^{a}	
	(**)	7.3	7.0			66.5	73.4			441.5^{b}	487.5^{a}		
Tutaekuri													
	60% ET	5.8	10.8	8.3	9.2^{bc}	19.8	27.4	23.6^{c}	30.2^{b}	119.0	244.0	181.5^{b}	233.5^{c}
	100% ET	13.8	6.5	10.1		25.1	48.7	36.9^{b}		330.0	241.0	285.5^{a}	
	(**)	9.8	8.6			22.5^{b}	38.0^{a}			224.5	242.5		
Moemoe													
	60% ET	9.3	11.8	10.5	14.3^{a}	39.0	39.4	39.2^{b}	34.6^{b}	331.3	334.8	333.0^{b}	400.4^{b}
	100% ET	15.8	20.3	18.0		34.2	25.8	30.0^{b}		432.5	503.3	467.9^{a}	
	(**)	12.5	16.0			36.6	32.6			381.9^{b}	419.0^{a}		
Sign.	Cultivars				P<0.0001				P<0.0001				P<0.0001
	Irrigation				Ns				P≤0.07				P<0.0001
	Nitrogen				Ns				Ns				P<0.01
	Cultivar*Irrigation				P<0.01				P<0.01				Ns
	Cult*Irr*N				P=0.01				Ns				P<0.01
$LSD_{0.05}$	Cultivar				2.8				16.1				46.5
	Nitrogen				-				-				32.9
	Irrigation				-				11.4				32.9

Note: Column rows with same letters are not significantly different. *N=16, **N=32.

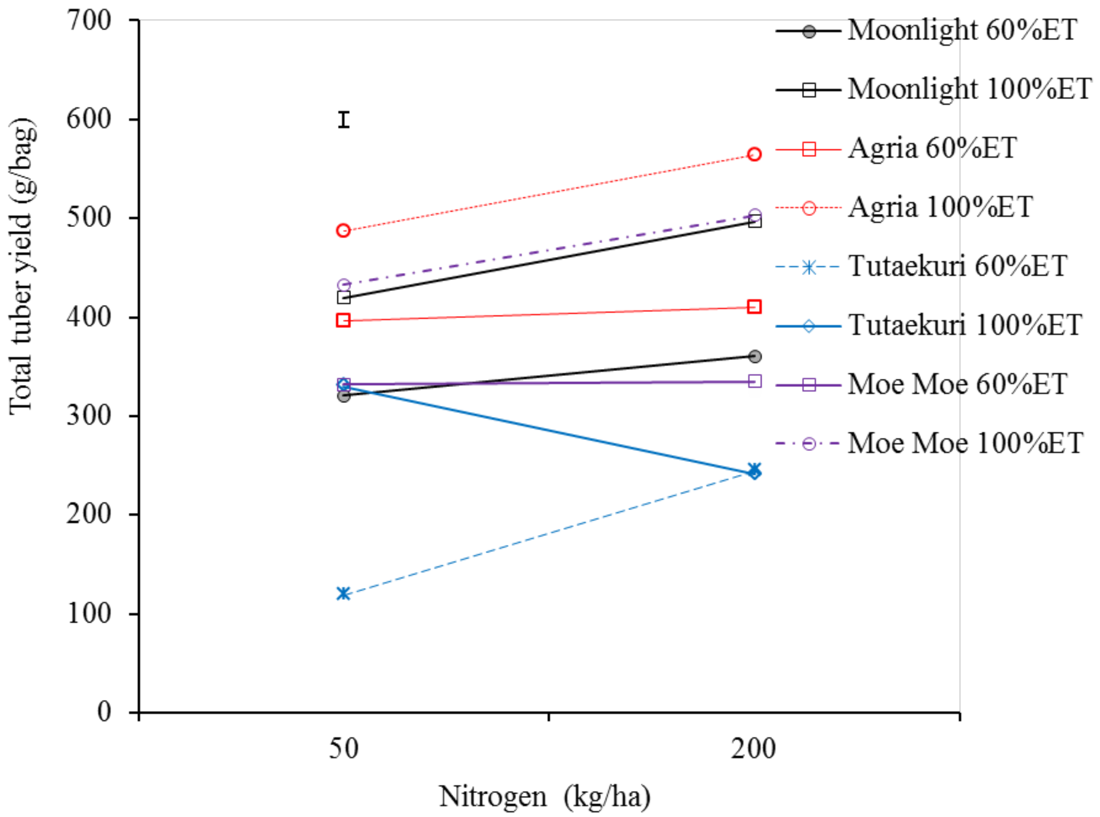


Figure 3.13 Interaction between cultivars, irrigation and nitrogen regime on total tuber yield (g/bag). Error bar represents ±SEM.

3.3.5: Water use efficiency and nitrogen use efficiency of four potato cultivars

Water use efficiency reflected tuber yields and it was highest in Agria, which was significantly (P<0.0001) higher than Moonlight and Moe Moe (Table 3.6). Water use efficiency of Tutaekuri was significantly lower than for all the other cultivars. Water use efficiency was also affected by irrigation and N in all cultivars, except Tutaekuri. Increasing irrigation, from 60% ET to 100% ET, reduced WUE by 12% in Moonlight, 15% in Agria and 9% in Moe Moe (Fig. 3.7). The high N fertiliser rate increased WUE by 15% in Moonlight, 9% in Agria, 8% in Moe Moe and 19% in Tutaekuri (Fig. 3.7). However, high N increased WUE at 60%ET while decreasing WUE at 100%ET (Fig. 3.7)

Similarly, NUE was significantly higher (P<0.0001) for Agria than Moe Moe and Moonlight, which were significantly higher than Tutaekuri. Nitrogen use efficiency was significantly affected by irrigation (P<0.0001) and N fertiliser (P<0.0001). There was a significant interaction between irrigation and N (P<0.0001) and between irrigation, N and cultivar (P<0.05) on NUE (Fig. 3.8 and Table 3.6). Increased irrigation increased NUE by 30% in Moonlight, 26% in Agria, 33% in Moe Moe and 104% in Tutaekuri. However, high N reduced NUE by 67% in Moonlight, 68% in Agria, 70% in Tutaekuri and 69% in Moe Moe.

The relationship between WUE and NUE was explored using a simple correlation. With all data combined, no correlation between WUE and NUE was found. However, when data were stratified by N treatments, moderately strong (P<0.01) correlations were identified: low N (r = 0.71) and high N (r = 0.72). Data stratified by irrigation analysis revealed no correlation between WUE and NUE.

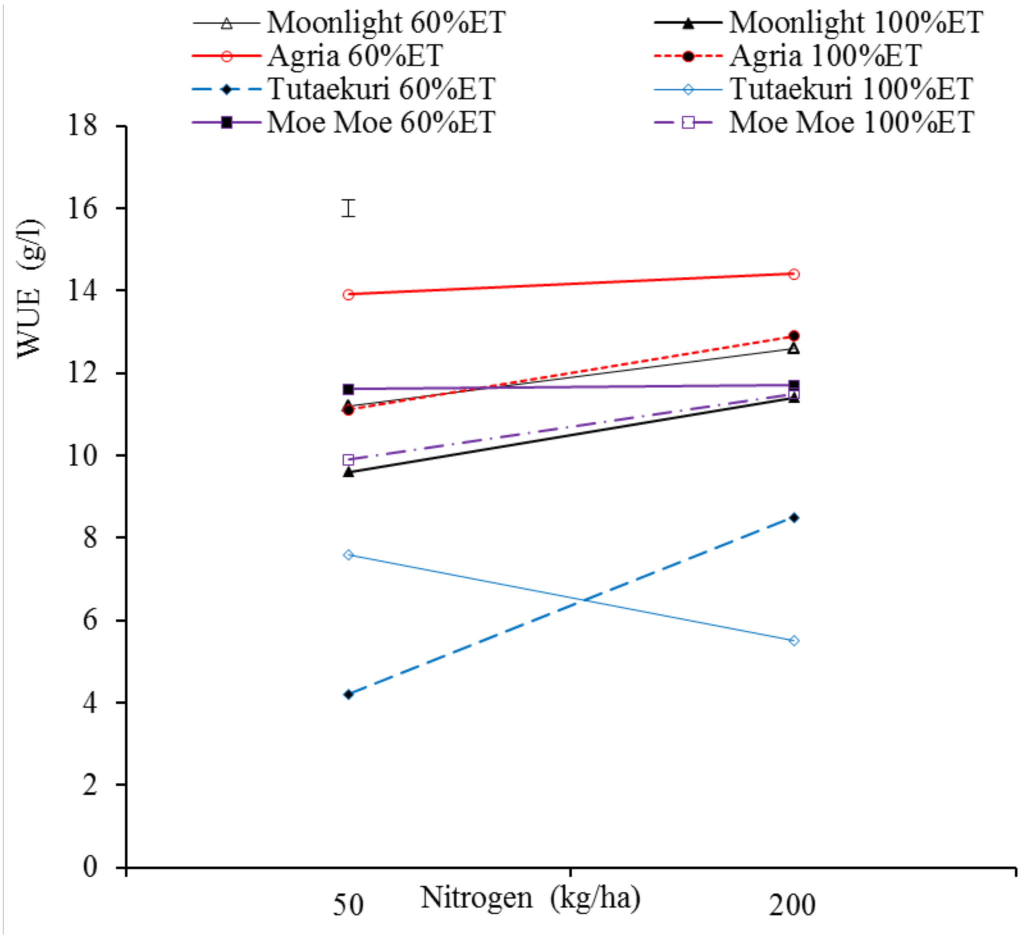


Figure 3.14 Interaction between cultivars, irrigation and nitrogen regime on WUE (g/ l). Error bar represents ±SEM.

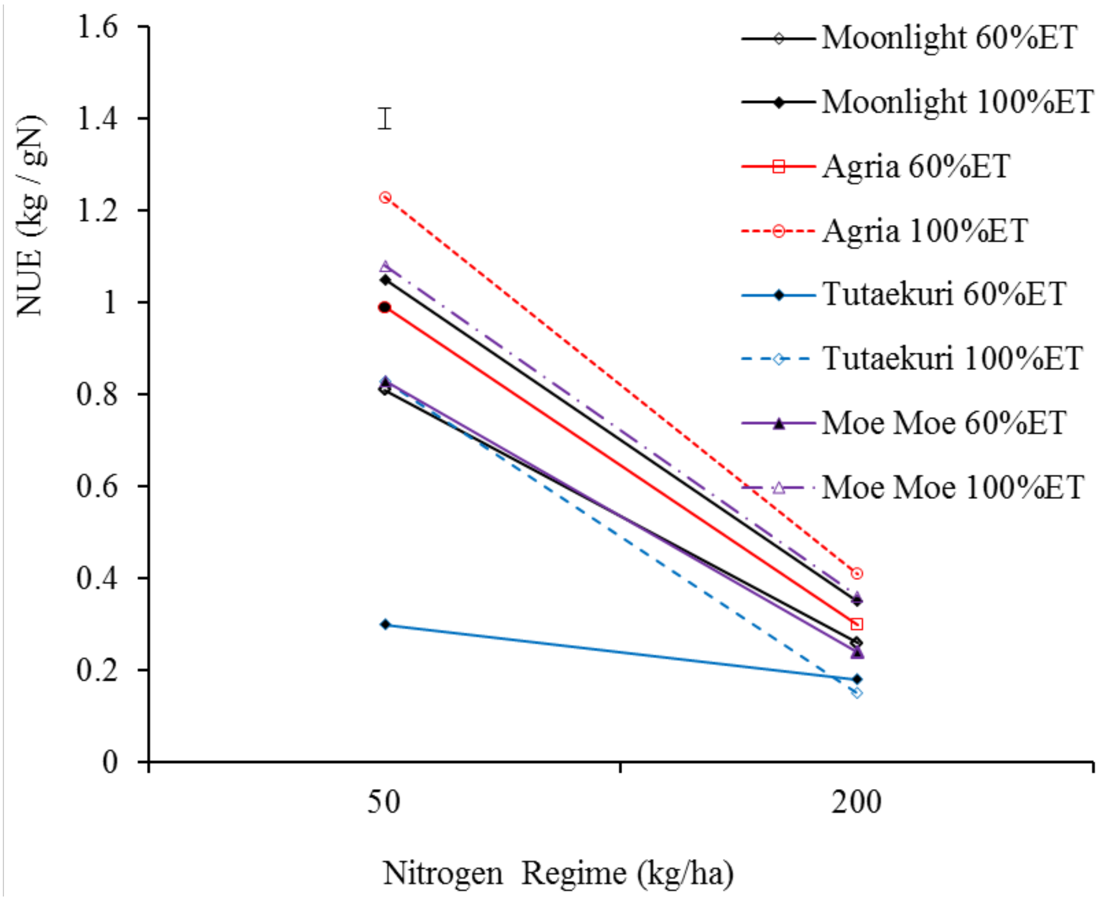
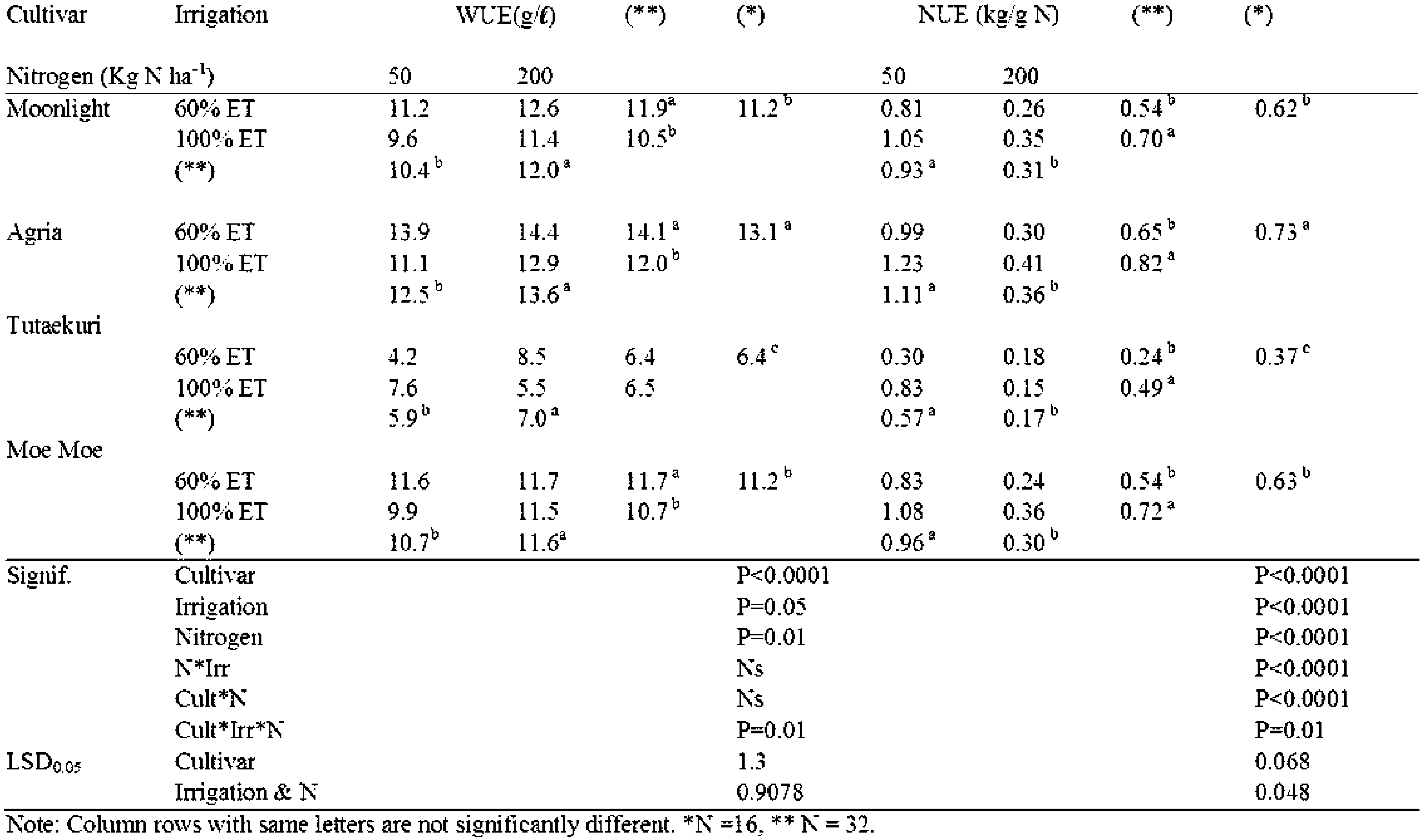


Figure 3. 15 Interaction between cultivars, irrigation and nitrogen regime on nitrogen use efficiency (NUE) (kg/gN). Error bar represents ±SEM.

Table 3.6 Water use efficiency (WUE) and nitrogen use efficiency (NUE) in four potato cultivars.



Cultivar	Irrigation	WUE(g/ℓ)		(**)	(*)	NUE (kg/g N)		(**)	(*)
Nitrogen (Kg N ha^{-1})		50	200			50	200		
Moonlight	60% ET	11.2	12.6	11.9^{a}	11.2^{b}	0.81	0.26	0.54^{b}	0.62^{b}
	100% ET	9.6	11.4	10.5^{b}		1.05	0.35	0.70^{a}	
	(**)	10.4^{b}	12.0^{a}			0.93^{a}	0.31^{b}		
Agria	60% ET	13.9	14.4	14.1^{a}	13.1^{a}	0.99	0.30	0.65^{b}	0.73^{a}
	100% ET	11.1	12.9	12.0^{b}		1.23	0.41	0.82^{a}	
	(**)	12.5^{b}	13.6^{a}			1.11^{a}	0.36^{b}		
Tutaekuri									
	60% ET	4.2	8.5	6.4	6.4^{c}	0.30	0.18	0.24^{b}	0.37^{c}
	100% ET	7.6	5.5	6.5		0.83	0.15	0.49^{a}	
	(**)	5.9^{b}	7.0^{a}			0.57^{a}	0.17^{b}		
Moe Moe									
	60% ET	11.6	11.7	11.7^{a}	11.2^{b}	0.83	0.24	0.54^{b}	0.63^{b}
	100% ET	9.9	11.5	10.7^{b}		1.08	0.36	0.72^{a}	
	(**)	10.7^{b}	11.6^{a}			0.96^{a}	0.30^{b}		
Signif.	Cultivar				P<0.0001				P<0.0001
	Irrigation				P=0.05				P<0.0001
	Nitrogen				P=0.01				P<0.0001
	N*Irr				Ns				P<0.0001
	Cult*N				Ns				P<0.0001
	Cult*Irr*N				P=0.01				P=0.01
LSD$_{0.05}$	Cultivar				1.3				0.068
	Irrigation & N				0.9078				0.048

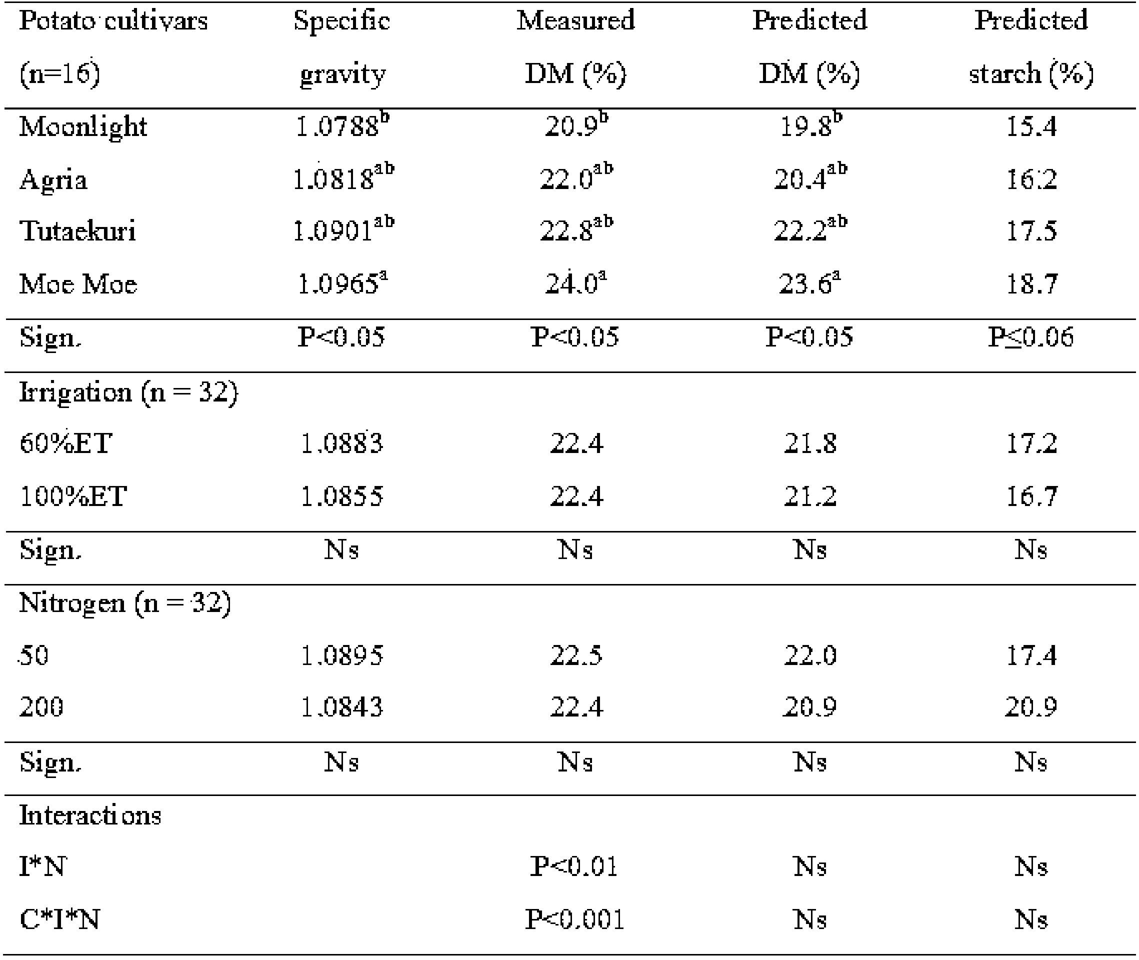
Note: Column rows with same letters are not significantly different. *N =16, ** N = 32.

3.3.6 Specific gravity and tuber dry matter content in four potato cultivars

Specific gravity and DM% were significantly affected by cultivar ($P<0.05$), but not by irrigation and N (Table 3.7, Appendix 3.3). Moe Moe had the highest SG and DM%, whilst Moonlight had the lowest SG and DM%, respectively. Significant interactions were observed for DM% between cultivars*irrigation*N ($P<0.001$) and irrigation*nitrogen ($P<0.01$). Appendix 3.3 shows that high N, with high irrigation, decreased DM%, compared to high N with low irrigation.

The interaction between cultivars*irrigation*N on DM% was very prominent for Tutaekuri (Appendix 3.3). The predicted starch content (%) was also highest in Taewa, although it was not significantly different from the modern cultivars ($P>0.05$). Specific gravity, amongst all cultivars, was highly positively correlated with the DM%. The SG and DM% relationship in the modern cultivar was linear, whereas the SG and DM% relationship in Taewa was curvilinear (Appendix 3.4). Agria DM% = 178.1(SG) - 170.64 $R^2 = 0.49$; Moonlight DM% = 206.3(SG) - 201.7, $R^2 = 0.91$; Moe Moe tDM% = - 3696.1$(SG)^2$ + 8249.2(SG) - 4576.1, $R^2 = 0.85$ and Tutaekuri DM% = -1638.2$(SG)^2$ + 3726.7(SG) - 2091.2, $R^2 = 0.94$ (Appendix 3.3). Measured DM% also had a moderately strong correlation with predicted starch content and predicted DM% ($r = 0.66$, $P<0.0001$). The cultivars with high SG, that being Taewa, had increased DM% and predicted starch content (Table 3.7, Appendix 3.3 ; Appendix 3.4).

Table 3.7 Specific gravity and tuber dry matter content of four potato cultivars in glasshouse experiment



Potato cultivars (n=16)	Specific gravity	Measured DM (%)	Predicted DM (%)	Predicted starch (%)
Moonlight	1.0788^{b}	20.9^{b}	19.8^{b}	15.4
Agria	1.0818^{ab}	22.0^{ab}	20.4^{ab}	16.2
Tutaekuri	1.0901^{ab}	22.8^{ab}	22.2^{ab}	17.5
Moe Moe	1.0965^{a}	24.0^{a}	23.6^{a}	18.7
Sign.	$P<0.05$	$P<0.05$	$P<0.05$	$P \leq 0.06$
Irrigation (n = 32)				
60%ET	1.0883	22.4	21.8	17.2
100%ET	1.0855	22.4	21.2	16.7
Sign.	Ns	Ns	Ns	Ns
Nitrogen (n = 32)				
50	1.0895	22.5	22.0	17.4
200	1.0843	22.4	20.9	20.9
Sign.	Ns	Ns	Ns	Ns
Interactions				
I*N		$P<0.01$	Ns	Ns
C*I*N		$P<0.001$	Ns	Ns

Note: Column rows with same letters are not significantly different.

3.4 Discussion

3.4.1 Evapotranspiration and volumetric soil water content

The results of this study show that Moonlight, Agria and Moe Moe extracted more soil water than Tutaekuri. This indicates potato cultivar differences in water extraction under different soil moisture regimes. Although the replacement of 100% evapotranspiration supplied adequate soil moisture to maintain field capacity, Tutaekuri gradually extracted less soil moisture. Consequently, the other three cultivars extracted more water from a greater depth within the low irrigation treatment, compared to the well watered conditions. The availability of water, the health state of plant and growth stages are the factors that influence soil water use within the soil profile (Stalham *et al.*, 2004). The ability of Tutaekuri to extract water may have been reduced by a potato leaf-roll viral disease (PLRV) infection that reduced its vigour (Ovenden *et al.*, 1985). Leaf curling and chlorosis caused by PLRV might have affected leaf water use and root water uptake in Tutaekuri.

3.4.2 Vegetative growth characteristics of Taewa and modern potato cultivars

3.4.2.1 Potato seed size and days to emergence

Taewa had small seed tubers which were late to emerge compared to the modern cultivars. The differences in emergence could be due to cultivar differences in dormancy or sprouting, as a response to low temperatures experienced during the winter (Mustonen, 2004). Potato cultivars differ in dormancy: those with the longest dormancy period are reported to be the latest to sprout (Bogucki *et al.*, 1980). Nevertheless, seed size and days to emergence hardly affected yield and yield components in this study, whereas other studies have reported low production (Wiersema *et al.*, 1986) and delayed emergence due to small seed (Mustonen, 2004). This result suggests that the difference in tuber seed size is probably due to genetics, rather than environmental conditions. On the other hand, germination was due to genetics and environmental factors interactions. Taewa might have longer dormancy compared to modern cultivars. The low temperatures in winter might have increased the dormancy in Taewa unlike modern cultivars which are bred to suit different environmental conditions.

3.4.2.2 Vegetative growth characteristics

Taewa cultivars were tall with a large leaf canopy, whilst the modern cultivars were shorter with a smaller leaf canopy. The large leaf canopy and leaf area in Taewa coincides with other findings in wheat (Siddique *et al.,* 1990a), soya bean (Frederick *et al.,* 1991) and oats (Ziska *et al.,* 2007), which concluded that heritage cultivars have greater vegetative growth than modern cultivars. Contrary to other reports, N and irrigation had little effect on other growth characteristics and flowering (Manochehr *et al.,* 2009). Moe Moe flowered earlier than the modern cultivar, Agria. This result suggests that the cultivar effect was greater than N or the irrigation's influence on vegetative growth characteristics within the glasshouse.

3.4.3 Photosynthetic WUE and gaseous exchange in Taewa and modern potato

Photosynthetic WUE and gaseous exchange were strongly influenced by cultivar, irrigation, N and DAE in this study, supporting earlier reports in potatoes (Ghosh *et al.,* 2000; Vos *et al.,* 1989a; Vos *et al.,* 1987). However, high N decreased A_n in Taewa, whilst it increased in the modern cultivars. Photosynthesis increased with irrigation increase in all cultivars, except Tutaekuri, which had high A_n at low irrigation. The high A_n in Taewa, compared to modern cultivars, may be due to the genotypic variation in stomatal and mesophyllic activity as also observed in old and modern Durum wheat by Koç *et al.* (2003). Taewa does not require a high amount of N for A_n maintenance. Nevertheless, optimal water is a requirement in Moe Moe and the modern potato for maximum gas exchange (Olesinski *et al.,* 1989).

Photosynthetic WUE and A_n initially increased before declining with time in all cultivars, regardless of irrigation and N treatment. A similar result has also been reported by Ghosh *et al.* (2000). Figures for photosynthetic WUE and A_n were remarkably high from days 20 to 50. Generally, modern potatoes had high A_n within the first three weeks from emergence, but Taewa high A_n was extended up to 65DAE (Appendix 3.2). The tendency for photosynthetic WUE and A_n decrease was greatest in the modern cultivars, Agria and Moonlight, possibly due to early maturity, compared to Taewa (Appendix 3.2). Ghosh *et al.* (2000) also reported high A_n within 20DAE and concluded that this period had raised A_n due to tuberisation. Moorby (1970) also reported a rise in A_n with tuberisation in potato. In this study, Taewa delayed tuberisation, hence their extended high gaseous exchange.

Taewa, achieved high photosynthetic WUE by maintaining high A_n at low g_s, T and Ci, compared to Agria and Moonlight (Appendix 3.2). Taewa and Moonlight had comparable g_s and T. However, A_n and photosynthetic WUE, in Moonlight and Agria, steadily reduced with water stress. The main driver of these differences was Ci, which was high in the modern cultivars and low in Taewa. Photosynthetic WUE is negatively correlated with Ci, particularly in modern cultivars. Consequently, its increase in modern cultivars reduced A_n and photosynthetic WUE. This finding agrees with other studies, which have indicated that increased C*i* reduces A_n (Morison, 1998). For this reason, Taewa differ from modern potato cultivars in photosynthetic WUE, in the way Ci manipulates stomata apertures. It is possible that modern cultivars have changed gaseous exchange behaviour through breeding (Morison, 1987), thereby resulting in disparity in photosynthetic WUE with heritage cultivars. Heritage cultivars have not undergone several breeding processes so gaseous exchange has not been modified (Vos *et al.,* 1989a).

Water deficit increases leaf VPD, which consequently reduces g_s and photosynthetic capacity (Malti *et al.,* 2002). In this study, the A_n, g_s and T increased with irrigation and N, whereas VPD and Ci declined with irrigation. It was also observed that VPD was significantly influenced by water deficit, thus resulting in low A_n and photosynthetic WUE. This shows that reduced irrigation, below optimal levels, affects gaseous exchange in both Taewa and modern potato cultivars; although this differs. Nevertheless, Taewa exhibited exceptionally high photosynthetic WUE characteristics under water stress. This ability suggests they are well adapted to low water supply.

3.4.4 Total tuber yield, water and nitrogen use efficiency

Moe Moe responded to irrigation and N primarily through an increase in tuber numbers, whereas Agria responded by producing few tubers with increased tuber weight. Increased yield, in response to irrigation and N, results from increased partitioning of assimilates to the roots and tubers, but the influence on yield components can vary with the cultivar (Bélanger *et al.,* 2002). The manipulation of irrigation and N enhances potato tuber yield through increased tuber numbers (MacKerron *et al.,* 1986) and tuber weight, but the mechanism varies with cultivar (Fig. 3.6 and Table 3.5).

The relatively poor yield of Tutaekuri, at 100% ET and high N, may have been the result of a virus infection in the plants used in this treatment combination (Ovenden *et al.,* 1985), as a result of infected seed tubers (Roskruge, pers. comm. 2010). The virus symptoms were present in Tutaekuri, whereas no virus symptoms were observed in the other cultivars. Consequently, manipulation of the environment may not affect yield and WUE in all genotypes (Steyn *et al.*, 1998). For this reason, growers need to consider all factors, including disease control, when seeking optimum resource use to maximise their profitability, because high WUE depends on these factors (Jefferies *et al.*, 1993b; Vos *et al.*, 1989b). Mean WUE varied with yield and it ranged from 13.1 g ℓ^{-1} (Agria) to 6.4 g ℓ^{-1} (Tutaekuri). This equates to 7.6 and 15.6 ℓ, respectively, to produce a 100 g tuber and it is lower than an estimate of the mean global virtual water content of 25 ℓ for a 100 g potato tuber (Hoekstra *et al.*, 2007). Irrigation and plant growth in the glasshouse was well controlled and this might have influenced lower virtual water content, rather than the mean global virtual content, which was estimated in the field.

Water use efficiency was highest under restricted irrigation, but a consequence of this situation was that NUE was reduced. Wang *et al*., (2009b) also reported that WUE was higher in partial root-zone drying and deficit irrigation, rather than that found in well watered potato crops, when full irrigation, partial root-zone drying and deficit irrigation were compared in a glasshouse environment. The integration of management utilises the correlation between WUE and NUE reported in this and other studies (Battilani *et al.*, 2004). The adoption of high yielding cultivars can be based on selecting cultivars with high WUE and high NUE, in addition to high soil water abstraction. In this study, tuber yield and WUE were relatively high in the three cultivars and WUE was affected by the irrigation regime, whereas the low yielding cultivar (Tutaekuri) had low WUE, irrespective of the irrigation level. This result suggests that manipulation of the environment might not affect yield and WUE in potato cultivars with low potential yield, so much as that in cultivars with a high potential yield (Steyn *et al*., 1998).

Tuber yield response to irrigation was greater than that of N. The requirement for adequate water in potatoes has been well documented (Ferreira *et al.,* 2007), whereas high rates of N can decrease the yield for potatoes (Manochehr *et al.*, 2009). During sunny days, the temperature in the glasshouse was generally above 20^{o}C and this suggests that evapotranspiration (and therefore the requirement for irrigation water estimated by *Brassica napus*) was adequate, especially when the potatoes were in full canopy. This result is supported by the high water extraction of soil moisture, by Agria, Moonlight and Moe Moe between days 20 and 50 (Fig.3.3).

Moe Moe showed similar productivity and resource use efficiency to Moonlight and Agria, despite the fact that it is a heritage cultivar. This result agrees with the suggestion that high tuber yield and WUE, which is apparent in most modern cultivars, relies on a combination of factors, including appropriate site selection, pest and disease control and the optimum management of inputs, rather than simple genetic improvements, in order to achieve high yield and WUE (Richards *et al.*, 2002; Barker *et al.*, 2003). The performance of Moe Moe indicates that, with appropriate management of inputs, its use may allow growers to access high value niche markets (McFarlane, 2007), without necessarily suffering low yields.

3.4.5 Specific gravity and tuber dry matter content

The values of SG, as a measure of DM in potato, are influenced by genotypes, environment and their interaction (Killick *et al.*, 1974; Jefferies *et al.*, 1993b; Kellock *et al.*, 2004). In this study, SG was not strongly affected by irrigation and N, but it was influenced by genotypes. The possible reason for this result may be that the moisture and N availability met the potato crop requirements (Bélanger *et al.*, 2002).

Taewa had high SG and DM, compared to the modern cultivars. Similar result has been previously reported by Singh *et al.* (2008), who found that Moe Moe (1.069, 21.9 %,) and Tutaekuri (1.074 21.6%) had higher SG and DM, than the modern cultivar, Nadine. However, the SG in Moe Moe and Tutaekuri, in this study, was very high compared to results reported by Kellock *et al.* (2004) and Verma *et al.*, (1971). Genetic factors and the late maturity of Taewa may increase the period of dry matter accumulation (Killick *et al.*, 1974).

Tutaekuri demonstrated that irrigation and N increases would steadily decrease DM (Appendix 3.3). This interaction is paramount for the use of SG in tuber quality determination in Taewa, because appendix 3.4 shows that SG is a surrogate trait to DM in tuber quality (Kellock *et al.*, 2004). These genotypic differences in tuber quality are essential for modern production systems, because they can be used to set standards of input management in Taewa and they can also provide genetic resources for improving modern potato processing quality. It is apparent that Taewa growers need to be aware of how they manipulate the soil moisture and N environment, in order to maintain a high level of tuber quality.

3.5 Conclusion

This study compared vegetative growth and gaseous exchange characteristics, yield and yield components, WUE and NUE, in Taewa and modern potato cultivars that were subjected to two different levels of irrigation and N, in the glasshouse. It was observed that Taewa had wide and tall stems with a large leaf canopy, whilst the modern cultivars had a prominent number of short stems with a small leaf cannopy. Photosynthetic WUE and A_n differed between cultivars and it decreased with time, regardless of irrigation and N treatment: with the highest photosynthetic WUE and A_n being observed in Taewa. It was also observed that Taewa had high DM and SG, compared to the modern potato cultivars.

The results also indicate that irrigation and N application improves Taewa and modern potato cultivars' yields. Total tuber yields were highest in Agria and Moe Moe: and this was a result of the high mean tuber weight and high tuber number per plant, respectively. Increased water supply increased yield and NUE, but it decreased WUE. Cultivars with high WUE also had high NUE. Subsequent field studies, on the same cultivars, will provide a more detailed insight into the effect of different water regimes on Taewa and modern potato cultivars, in relation to their physiological characteristics, yield, WUE and NUE.

CHAPTER 4

COMPARISON OF MODERN AND HERITAGE POTATO, OCA AND PUMPKIN SQUASH CULTIVARS’ RESPONSE TO IRRIGATION AND RAINFALL IN THE FIELD

4.1 Background

The glasshouse experiment results in Chapter 3 indicated substantial differences in yield and WUE between some Taewa and modern potato cultivars. The yield response to an increase in irrigation (60% ET to 100% ET) suggests that, in the field, irrigation could affect heritage and modern crop cultivars differently. Therefore, further understanding of water use in Taewa and modern potato cultivars (*Solanum tuberosum ssp. Tuberosum* L and *Solanum tuberosum ssp. andigena Juz. & Buk.*) and other heritage crops, where there is renewed commercial interest, such as oca or New Zealand yam (*Oxalis tuberosa* Mol.) and pumpkin squash, Buttercup squash (C*ucurbita maxima* Duchesne.*)* and Kamokamo *(Cucurbita pepo* Linn) in the field is crucial. However, no field study has been conducted to quantify and compare the yield-water use functions and water footprint of Taewa and modern potato and oca and pumpkin squash cultivars, under irrigation in New Zealand.

The field experiment reported in this chapter was conducted in order to measure and compare yield, physiological characteristics and water use efficiency indicators (irrigation water use efficiency, economic water productivity and water footprint) of heritage and modern potato, oca and pumpkin squash cultivars, under rain-fed and irrigation in the field in New Zealand. The change of production, from crop enterprises with low water productivity to enterprises with high water productivity, would reduce the water footprint at farm level, in addition to increasing profits.

4.2 General materials and methods

4.2.1 Experimental site

The field experiment was conducted at Massey University’s Pasture and Crop Research Unit, Palmerston North, commencing on 10th November 2009. The site is located at a latitude of 40^{o} 22. 54.02 S, longitude 175^{o} 36’ 22.80 E, and an altitude of 36 m above sea-level. The soil type is Manawatu sandy loam. There were 106 kg ha^{-1} of available N and 76.8 mg N kg^{-1} of soil anaerobically mineralised N at the beginning of the experiment. Other soil chemical characteristics (Olsen P, K, organic matter content, and pH) for the paddock are shown in Table 4.1. The maximum and minimum temperature and rainfall collected by the metereorology station for the site during the season is presented in Fig. 4.1.1.

Table 4.1 Soil chemical characteristics: pH, applied nitrogen (N), Olsen phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and cation exchange capacity (CEC) for the site as of 10th November, 2009

pH	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Na (mg/kg)	CEC (me/100g)
5.4	76.8	36	86.0	1380	146.4	27.6	14

4.2.2 Experimental layout and crop management

The experiment, which consisted of four potato cultivars (*Solanum tuberosum* L., *Solanum tuberosum ssp. andigena* Juz & Buk.), two oca or New Zealand yams (*Oxalis tuberosa* Mol.) and two pumpkin squash varieties (*Curcubita pepo* Linn and C*ucurbuta maxima* Duchesne) was laid out as a split-plot design, with water regimes as the main plots (rain-fed and irrigation treatments), each being randomised and replicated four times. The crop cultivars were subplots. The four potato cultivars were two modern cultivars (Agria and Moonlight (*S. tuberosum L.*) and two Taewa [Moe Moe (*S. tuberosum L.*) and Tutaekuri (*S. tuberosum ssp. andigena* Juz & Buk.)]. The two pumpkin squash cultivars were buttercup squash, Ebisu (C. *maxima* Duchesne, a modern cultivar) and a heritage pumpkin cultivar, Kamokamo (*C. pepo* Linn,), whilst two unnamed oca cultivars with dark orange and scarlet coloured tubers (both heritage cultivars) were used. Each crop cultivar was replicated four times per water regime and eight times in the entire experiment (Fig. 4.1).

Amongst the potato cultivars, Moe Moe has a multi-coloured skin with creamy patterned flesh whilst Tutaekuli has long-yam-like tubers with dark purple flesh, both with haulms maturing in 160 - 180 days (Harris *et al.*, 1999; Hayward, 2002). Agria and Moonlight are dual-purpose main-crop potato cultivars with haulms maturing in 140-150 days (Anderson *et al.,* 2004, Plate 3.1). Taewa seed tubers were from Maori Resource Centre whilst modern potato seed tubers were obtained from the potato seed company, ‘Morgan Laurenson Ltd’. Certified Buttercup squash seed were sourced from

'Massey Seed Technology' section while certified Kamokamo seed was purchased from 'Kings Seed Company'. Oca seed tubers were locally sourced from a New Zealand farmer.

4.2.3 Plot-size and plant spacing

Potato tubers were manually sown on 10th November, 2009, at 75 cm spacing between rows and 40 cm spacing within rows at a depth of 10 - 15 cm. Each plot was 6 m by 1.5 m and each plot held 30 plants. Each plot had two guard rows planted with the Desiree variety. Oca was also manually sown on 10th November 2009, in rows spaced at 75 cm and with 35 cm between seed tubers, with one tuber per station, in a 10 - 15 cm deep furrow that was opened by machine. The gross plot was 6 m by 3 m and the net plot was 6 m by 1.50 m, each with 34 plants. Pumpkin squash cultivars were manually sown on 9th December, 2009 at a spacing of 75 cm between rows, with 60 cm between plants and one plant per station, at a depth of 25 mm. Each plot (4.5 m by 6 m) had four rows of 6 m each, with 10 planting stations (Plate 4.1, Figure 4.1).

4.2.4 Fertiliser application and plant protection

The potatoes and oca received 12N:5.2P:14K:6S+2Mg+5Ca, using 500 kg Nitrophoska Blue TE at planting and this was followed by 100 kg N ha^{-1} of urea, as a side dressing, on 15thDecember 2009. The pumpkin squash received 12N:5.2P:14K:6S+2Mg+5Ca, using 700 kg ha^{-1} Nitrophoska Blue TE at planting, followed by 66 kg N ha^{-1}, as a side dressing, on 19th January 2010, when the vines started running. Mounding was done once during the season, when the plants had reached about 15 - 20 cm height (McKenzie, 1999).

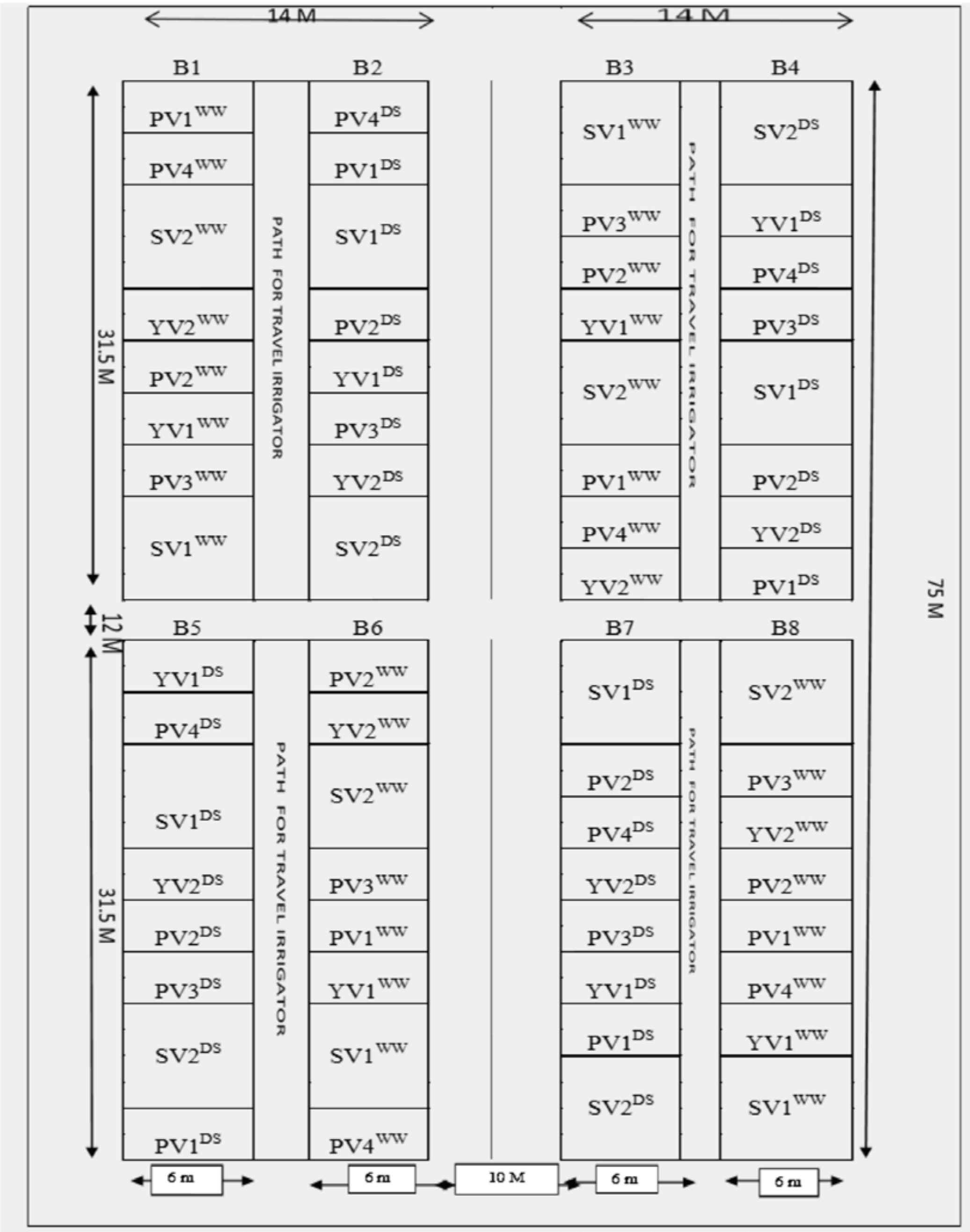
Weeds were initially managed by pre-emergence herbicides and secondary weeds were manually controlled. Leopard herbicide with 100 gl^{-1} Quizalofop-P-ethyl active ingredients and 812 gL^{-1} hydrocarbon liquid as a solvent was applied at 500 ml ha^{-1} to control couch grass also known as Elymus repens (*Cynodon dactaylon*). Gesagard 480SC herbicide with 480 gL^{-1} Prometryn and 1, 2-benzisothiazolin-3-one at 0.019% was applied as a preservative at 3.75L ha^{-1} to control other annual broad-leaved weeds, using 100 - 200 litres of water per hectare.

Chlorothalonil Tetrachloroiophthalonitrile (Bravo ULTREX SDG90), a broad spectrum fungicide, was sprayed in a mixture with 600 g/litre Methamidophos (Metafort 60SL), which is an organo-phosphorus insecticide, in order to control fungal diseases and insect pests; powderly mildew (*Erysiphe cichoracearum,* Jaczewski); early blight (*Alternaria solani,* Ellis & G. Martin) and late blight (*Phythophthora infestans,* Mont.); bacterial diseases (*Pseudomonas solancearum,* Smith); potato pest insects; potato psyllid (*Bactericera cockerelli* Sulc); potato aphids (*Macrosiphum euphorbiae,* Thomas); and potato tuber moth (*Phthorimaea operculella,* Tomohiro Ono) in potato and pumpkin squash. Metafort 60SL was sprayed at 800 ml ha^{-1}, in 500-1000 litres of water per hectare, every 14 days.

4.2.5 Irrigation system and irrigation scheduling

4.2.5.1 Irrigation system

The Trail T150-2 traveller irrigator (Plate 4.1a), with a 52 mm * 100 m angus premium Hi-Flow hose pipe and a minimum pull at 582 kPa (70 psi), was installed in the paddock, for an irrigation block system of 6 m width each side (Fig.4.1). The irrigator tapped water from the main supply line through a long polythene pipeline that was connected to its hydrant. The irrigator was running on a 2 m wide irrigation lane between two blocks and it applied water to 6 m on either side (Fig. 4.1). Each arm of the irrigator consisted of four low pressure sprinklers (10 psi), with a sprinkler nozzle diameter of 16 m, thus giving triple coverage in order to improve uniformity. The design application depth for the irrigator is approximately 40 mm hr^{-1}. However; the irrigator's speed was adjusted to 6 m hr^{-1} to give an actual application depth, per pass, of 25 mm. The water supply for the entire field was controlled at the hydrant, whilst for each treatment it was controlled through valves on the irrigator.



NOTE : PV1-PV4 refers to potato varieties: Moonlight, Agria, Tutaekuri and Moemoe,

YV1-YV2 refers to New Zealand oca varieties: Dark Orange and Scarlet, respectively

SVI-SV2 refers to Squash varieties: Ebisu and Kamokamo, respectively

WW refers to well watered treatment

DS refers to Non-irrigated or rain-fed treatment

Figure 4.1 Schematic diagram of the 1st field experiment layout [horizontal scale 1:300 and vertical scale 1:400]

4.2.5.2 Crop water use and soil moisture measurement

A soil water balance was used to determine the soil moisture deficit (SMD) on a daily basis during the growth of the crops (Premrov *et al.*, 2010). The potential evapotranspiration (ETp) in the soil water balance was computed for crops using the FAO 56 Penman-Monteith method (Allen *et al.*, 1998; Kassam *et al.*, 2001). The crop coefficient factors used in the crop water use computation were for potato, because this was the most sensitive crop to water use (Shock *et al.*, 2007). The daily weather data, for running the soil water balance model, were collected weekly from NIWA/AgResearch climate site, Palmerston North.

The soil water balance was used to schedule irrigation events and to calculate the quantity of drainage (D_p) over the growing period. The irrigation treatment was based on refilling 25 mm of the soil's moisture deficit (SMD) on the day that soil moisture deficit equated or exceeded 30 mm. This schedule was based on supplying approximately half the 'readily available water' held by the soil at the site, Manawatu fine sandy loam.

The actual crop evapotranspiration (ET_c) was determined using equation 4.1 (Allen *et al.*, 1998). Soil moisture change (ΔS) was the difference between soil moisture content at the end and the start of the field experiment as measured using a Time-Domain Reflectometer [TDR, model 1502C, Tektronix Inc., Beaverton, OR, USA] In addition to measuring soil water content at the start and conclusion of the trial, it was also monitored before irrigation and 24 hours after irrigation to a depth of 50 cm. As the site was flat and the crops were in the ground for the summer/autumn period, surface runoff (R_o) can be ignored.

$$ETc = P + I - D_p - R_o + \Delta S \qquad \text{Equation 4.1}$$

The total crop water use or consumption water use (CWU) for the entire growing cycle, for irrigation and rain-fed treatments, were referred to as blue and green components, respectively. The CWU was determined according to Hoekstra *et al.* (2009), as in equation 4.2: Where $\sum ETcblue$ and $\sum ETc\ green$ is the accumulation of actual water use (evapotranspiration) over the complete growing cycle for irrigated and rain-fed crops, respectively. Factor of 10 is required to convert water depths of mm into volume in $m^3\ ha^{-1}$ (Hoekstra *et al.*, 2009).

$$CWU_{blue+green} = 10 * \sum ETcblue + ETcgreen \qquad \text{Equation 4.2}$$

$$CWUgreen = 10 * \sum ETgreen$$

4.2.6 Morphological and physiological characteristics measurements

4.2.6.1 Vegetative growth characteristics of Taewa and modern potato cultivars

During the 2009 /2010 field trial, leaf features (the number of compound leaves per plant, LAI, SLA (cm^2g^{-1}), canopy cover and leaf dry weight per plant were measured at 32, 72, 95 and 128 days after emergence (DAE). The plant height (cm); number of stems per plant; number of branches per plant; and stem diameter at soil collar (mm), were measured after 100 days from planting. The LAI, leaf dry matter content (LDMC), SLA and crop canopy were measured according to Amanullah *et al.* (2007), Vile *et al.* (2005) and Ertek *et al.* (2006), as presented in Chapter 3.

4.2.6.2 Photosynthetic water use efficiency and gaseous exchange

Gaseous exchange was measured four times between 20 and 90 days, in potato and oca, after plant emergence, using CIRAS-2 (a portable photosynthesis system V2.01) (Plate 5.1a). Leaf stomata conductance (m molCO$_2$ m^2 s^{-1}); net photosynthesis (µmolCO$_2$ m^2 s^{-1}); transpiration rate (m molH$_2$O m^2 s^{-1}); internal CO$_2$ concentration (ppm); leaf vapour pressure deficit (bars) and leaf temperature (C^o) were recorded between 1000 - 1200 hrs, on newly expanded leaves (3rd leaf on main axis). Photosynthetic water use efficiency (Photosynthetic WUE) (µmolCO$_2$/m molH$_2$O) was determined as the ratio of net photosynthesis to transpiration rate (Xu & Hsiao, 2004; Liu *et al.,* 2006b). Photosynthetic Active Radiation (µmol photons m^2 s^{-1}) and reference CO$_2$ (ppm) were respectively maintained at an average of 1400 and 400, during all the CIRAS measurements. The measurements took 1-2 minutes per plant.

4.2.6.3 Leaf water potential of Taewa and modern potato cultivars

Leaf water potential (Ψ_w) was measured in potato using the Scholander pressure chamber method [Soil Moisture Equipment Corp., Santa Barbara, CA, USA] on both irrigated and non-irrigated plants (Boyer 1995; Plate 5.1b). It was measured at 2:00 pm, two days after irrigation application. A leaf to be measured was cut out using a scalpel, and then partly sealed in the pressure chamber. The chamber was pressurised with compressed gas until the distribution of water by the living cell and the xylem appeared on the open end of the xylem conduits: and the pressure used to release the droplets was then recorded (Boyer, 1995).

4.2.6.4 Dry matter production and partitioning characteristics in potato cultivars

Above-ground (leaves and stems) and below-ground biomass (roots and tubers) were sampled before plant senescence. Samples were collected on 18th February 2010, 100 days after planting. A small and a larger plant sample were randomly uprooted from each plot, using a spade. The plants were partitioned into leaves, stems, roots and tubers and then weighed and oven dried at 70°C, until there was no more change in the dry matter content (DM) (Bélanger *et al.,* 2001; Geremew *et al.,* 2007).

The ratio of each partition to total biomass (leaves, stems, roots and tubers) per plant was determined. Root/shoot ratio was determined as dry weight for roots divided by dry weight of above-ground biomass (leaves +stems biomass) (Siddique *et al.,* 1990b). Harvest index was calculated as the ratio of total tuber yield to total biomass production on dry matter basis from the samples of each plot, 100 days after planting and again at the final harvest (Mackerron *et al.,* 1985).

4.2.6.5 Tuber growth and development measurements in oca

Tuber development for oca was monitored 100, 132, 154, 174 and 224 days after planting (DAP). One poor and one well developed plant sample were randomly uprooted from each plot using a spade and partitioned into shoots and tubers, before being dried in an oven for 72 hrs at 70 °C, in order to determine dry matter (Bélanger *et al.,* 2001). The tuber growth rate per day was determined as the ratio of tuber fresh biomass (g) and the number of days taken to accumulate tuber fresh biomass (Plaisted, 1957).

4.2.7 Final total yield and yield components measurements

4.2.7.1 Total yield and marketable yield for oca, potato and pumpkin squash

Pumpkin squash (Buttercup and Kamokamo) were harvested on 29th and 31st March 2010, respectively. At harvest, fruit yield (kg); the number of fruits per plant; individual fruit weight; fruit yield; and total biomass were measured. Pumpkin squash fruits were graded into marketable and non-marketable grades (NM): marketable fruit was above 1kg, without any damage and non-marketable were fruit <1kg and fruit with damage. Marketable fruit was further graded as S (1-1.2 kg), M (1.2-1.4 kg), L (1.4-2.5 kg) and XL (>0.2.5kg), where S is small, M is medium, L is large and XL is extra-large, according to export quality grades in New Zealand by Leaderbrand Produce Limited. (http://www.leaderbrand.co.nz/Buttercup_Squash_(Kabocha)55.aspx)

Potato was harvested on 17th May, 2010, whilst oca was harvested on 22nd June, 2010. At harvest, the total fresh tuber yield (kg); marketable tuber yield; number of tubers per plant; and average tuber weight per plant were measured. Potato and oca tubers were later graded into marketable and non-marketable grades. Oca marketable tubers were above 12.5 g, without any damage and non-marketable tubers were <12.5 g and tubers with damage. Marketable tubers were further graded as medium (M) (12.5-<25.0 g) and large size grade (L) (>25 g), according to marketable quality grades in New Zealand (Osborne, 2010 Pers. Com.,). Potato marketable tubers were those above 55 g, without any damage and non-marketable were those <55 g and those with damage (Roskruge & McFarlane, 2010 Pers. Com.,). Marketable potato tubers were not further graded.

At harvest, shoot biomass (vines + leaves) was measured from five sample plants of each plot in potato, oca and pumpkin squash. Harvest index was calculated as the ratio of total tuber or fruit yield to total biomass production on dry matter basis, from the five samples taken from each plot (Mackerron *et al.*, 1985). The total biomass was the sum of dry harvestable yield and shoot biomass (vines + leaves).

4.2.7.2 Determination of specific gravity, DM and total sugars

Specific gravity and DM of potato were determined on ten tubers according to Haase, (2003), as presented in Chapter 3 (Plate 3.1). After SG measurements and DM determination, total sugar was determined from the eight composite samples above. Potato samples of 0.5 g were taken from the outer equatorial portion of each tuber of the ten tubers, excluding the skin, giving 2.5 g fresh weight for composite samples for each experimental plot before sending them to Massey Animal Nutrition Laboratory. The total sugars were extracted with aqueous alcohol and determined by using Pheno-sulphuric acid colorimetry at Massey Animal Nutrition Laboratory (Hall *et al.*, 1999).

4.2.8 Determination of efficient water use: key indicators

4.2.8.1 Irrigation water use efficiency and water stress factors

Irrigation water use efficiency (IWUE) was defined as the total yield difference between irrigation (Yns) and rain-fed (Yds) divided by the net evapotranspiration from irrigated crops (Ii) according to Howell, (2001). The IWUE was used for assessing contrasting crop cultivars' performance with increasing water use, using regression analysis (Ferreira *et al.*, 2007). The IWUE equation 4.4 took into account the contribution of irrigation to yield production for each crop cultivar tested in this experiment (Howell, 2001):

$$\text{IWUE} = \frac{Yns - Yds}{Ii} \qquad \text{Equation 4.4}$$

The effect of water stress on rain-fed crops was determined by a drought intensity index (DII) according to Ramirez-Vallejo *et al.*, (1998) as DII = 1 - $\frac{Yds}{Yns}$: Where Yds is the mean experimental yield of all cultivars from the same crop grown under rain-fed conditions and Yns is the mean experimental yield of all cultivars from the same crop grown under irrigation (Ramirez-Valejo *et al.*, 1998). The DII >0.7 indicated severe water stress. Geometrical mean yield was determined as GM =$\sqrt{Yds * Yns}$ to predict cultivar performance under water stress and non-stressed environment (Ramirez-Vallejo *et al.*, 1998; de Souza Lambert, 2006). The yield reduction (PR %) due to water stress under rain-fed, in relation to the irrigated environment, was determined as PR% =$\{\frac{Yns-Yds}{Yns} x\ 100\%\}$, where Y_{sd} and Y_{ns} are the yield of a given cultivar in a rain-fed and irrigated environment, respectively (Ramirez-Vallejo *et al.*, 1998). Water stress factors such as geometrical mean, DII and yield reduction were used to determine genotypical variations under water stress and well watered environments (Ramirez-Vallejo & Kelly *et al.*, 1998; de Souza Lambert, 2006).

4.2.8.2 Economic water productivity for heritage and modern crop cultivars

The economic water productivity index (NZ$/m^3) was assessed as the overall present value of each crop's marketable produce (NZ$) divided by the volume of water (m^3) consumed by the plant (Barker *et al.*, 2003; Molden *et al.*, 2001). The average crop prices used were those supplied by 'Statistics New Zealand', (2010) (http://www.stats.govt.nz) and personal communication (Osborne, 2010) for oca. Kamokamo and Taewa prices were found at 'Pak & Save supermarket', Palmerston North (2010) and by personal communication (Roskruge, 2010).

4.2.8.3 Water footprint of growing heritage and modern crop cultivars

The water footprint (WF) (m^{3}tonne^{-1}), defined as the volume of water required to produce a given weight or volume of oca, potato and pumpkin squash (t ha^{-1}), in New Zealand, was determined as the ratio of consumptive water use (CWU m^3 ha^{-1}) plus grey water to the total crop yield (t ha^{-1}) according to Hoekstra *et al.*, (2009). The total water footprint is the sum of blue (irrigation), green (rainwater) and grey water footprints. The blue and green water footprint (m^3 tonne^{-1}) was a ratio of blue and green crop water use (mm) to the total yield, respectively (Mekonnen *et al.*, 2010ab). The blue plus green water footprint was referred to as the consumptive water footprint (Chapagain *et al.*, 2005). Grey water is the additional water required to dilute or attenuate any fertiliser and pesticide pollution to an acceptable level in the receiving water body (Clothier *et al.*, 2010).

The grey water footprint (m^3 tonne^{-1}) was determined as the ratio of the total volume of water (m^3) required for diluting N that is leached, per tonne of produce (Chapagain *et al.*, 2005). The grey water footprint was estimated by multiplying the leaching fraction by the applied N (kg ha^{-1}) and dividing the difference between the permissible limit and natural concentration of N in the receiving water body (Hoekstra *et al.*, 2009). This study assumed a natural water nitrate concentration of 5.6 milligrams per litre and a permissible limit of 11.3 milligrams per litre (Daughney *et al.*, 2009). The leaching fraction of the 160 kg and 150 kg ha^{-1} applied N, for potato or oca and pumpkin squash cultivars, was assumed to be 10 - 15% (Chapagain *et al.*, 2005, Mekonnen *et al.*, 2010a). The study compared the water footprint based on actual crop yield and crop water use, in order to remove the disparity of over-estimation, when hypothetical crop and crop water requirements are used (Kumar *et al.*, 2007; Maes, 2009).

4.2.9 Statistical analysis

The data on physiological characteristics, total fresh tuber or fruit yield and marketable yield, were initially analysed separately for each crop. Subsequently, crop water use and total yield from the three crops were pooled, in order to determine their comparative irrigation water use efficiency, the stress indicators, water footprint and economic water productivity. The data was analysed by the GLM procedure of the SAS (SAS, 2008) and differences amongst treatment means were compared by the LSD, at 5% probability (Meier, 2006).

The RCBD split-plot linear statistical model used in GLM procedure was as follows:

$$¥ijk = µ + Î_i+β_j+(Îβ)_{ij}+Ŧ_k+(ÎŦ)_{ik}+(βŦ)_{jk}+(ÎβŦ)_{ijk}+Ę_{ijk};$$

Where, $µ$ is the overall mean, $Î_i$, $β_j$, $(Îβ)_{ij}$ represents the whole plot as irrigation, block and whole plot error effects; $Ŧ_k$, $(ÎŦ)_{ik}$, $(βŦ)_{jk}$ represents subplots as cultivars' effects, block effects and subplot errors; $(ÎβŦ)_{ijk}$ represents whole plot and subplot interaction effects; and $Ę_{ijk}$ represents overall error, respectively, whilst i= 1-2 water regimes, j=1-4 replicates and k=1-8 crop cultivars.

4.3 Results

The results and discussions for this chapter are presented in four sections, which cover the physiological characteristics and yield response of Taewa and modern potato (Section 4.3.1), oca (Section 4.3.2) and pumpkin squash (Section 4.3.3) to irrigation. Finally, there is a comparison of key water use efficiency indicators in heritage and modern potato, oca and pumpkin squash (Section 4.3.4).

(a) Potato, oca and pumpkin squash on blocks irrigated by travel irrigator and others non irrigated

(b) Pumpkin squash plot

(c) Oca plot

Plate 4.1 : Irrigation and heritage and modern crop cultivars layout at field level in 2009/2010

SECTION 4.3.1

TAEWA AND MODERN POTATO CULTIVARS’ RESPONSE TO IRRIGATION AND RAIN-FED CONDITIONS

4.3.1.1 Introduction

Potato production and yields have expanded in New Zealand and in the Pacific region, due to the introduction of modern varieties, improved cultivation, market access and differences in consumer preferences (Pandey, 2008). It is a subject of debate whether the potato yield increase is really a consequence of breeding or agronomic practices — or their interaction, or part thereof. Low yields and yield erosion of old potato cultivars are some of the reason that these cultivars are being substituted by modern cultivars (*Solanum tuberosum)* (Harris *et al.,* 1999). This is also happening with other heritage crops, such as *Brassica napus* ssp. *Napobrassica* (Gowers *et al.,* 2006), wheat (Siddique *et al.,* 1990a) and soybean (Frederick *et al.,* 1991). Regardless of substantial advancement in modern potato production, other quality traits for Taewa have attracted the interest of growers and consumers (McFarlane, 2007; Lambert, 2008). The results reported in this section are on Taewa physiological and morphological characteristics, tuber yield and WUE compared to modern potato cultivars under irrigation and rain-fed conditions in the field.

4.3.1.2 Materials and methods

All details of Taewa and modern potato experiment methodologies are presented in the general methodology section 4.2 above. This section presents the results on plant physiological and morphological characteristics, tuber yield and WUE for Taewa and modern potatoes only.

4.3.1.3 Results

4.3.1.3.1 Crop evapotranspiration, precipitation and irrigation

The growing season for Taewa and modern potato were 179 and 132 days, with a seasonal potential crop water requirement of 610 mm and 550 mm, respectively (Appendix 4.1.1). Precipitation supplied 69% of the potential water requirement

(Fig.4.1.1). The irrigated potatoes received 200 mm of irrigation water, which met at least 100% of the potential crop water requirement. The average crop water use for the rain-fed crop was 65.1% of the irrigated potato (Appendix 4.1.1). Finally, crop water use for the modern potato cultivars was 91.6% and 88.6% of that used by Taewa under irrigation and rain-fed environment, respectively (Appendix 4.1.1).

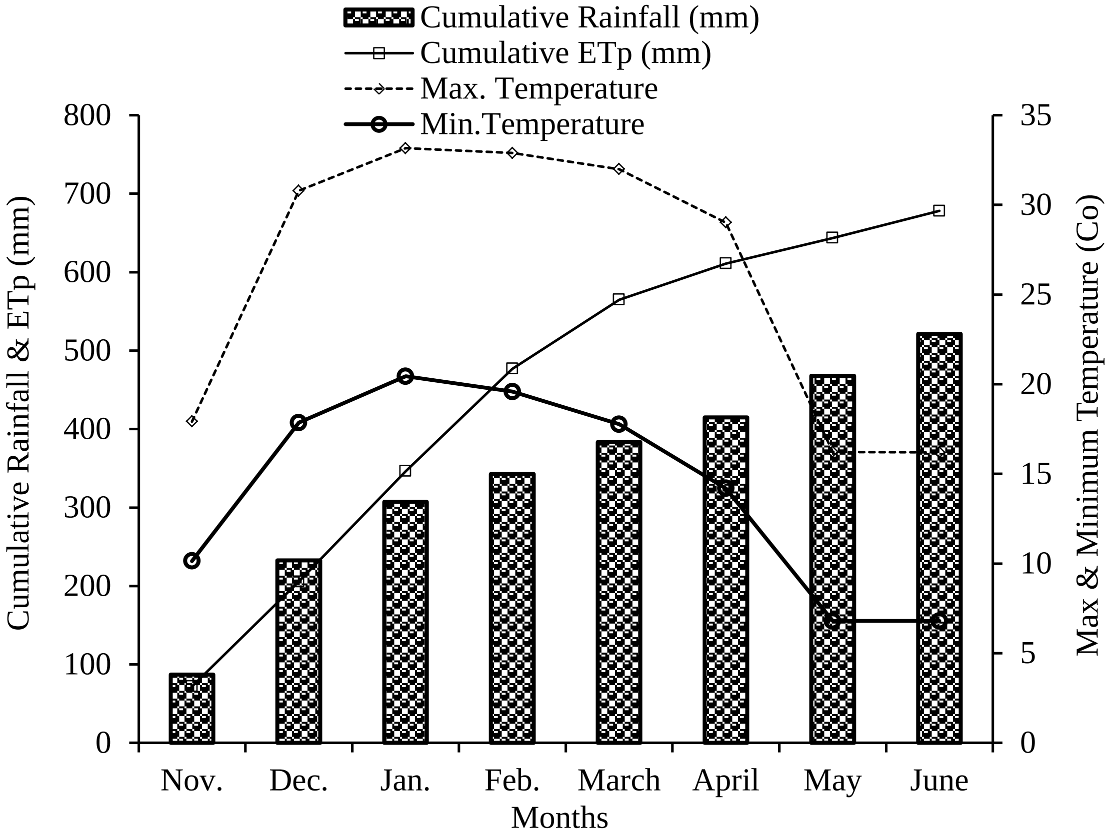


Figure 4.1.1 Cumulative rainfall (mm), cumulative potential crop evapotranspiration (ETp) (mm), monthly average maximum and minimum temperatures (°C) for the experimental site, during the experiment period from November 2009 to June 2010

4.3.1.3.2 Volumetric soil water content (%)

Since precipitation was not well distributed during the growing season, irrigation reduced the soil moisture deficit, (Fig. 4.1.2; Appendix 4.4.2). This was verified by the significant differences in the volumetric soil moisture content (%) between water regimes, crop cultivars and measurement dates ($P<0.0001$). Volumetric soil moisture content (%) in rain-fed was lower and it ranged between 15-20%, whilst irrigated treatments ranged between 20-35% (Fig. 4.1.2).

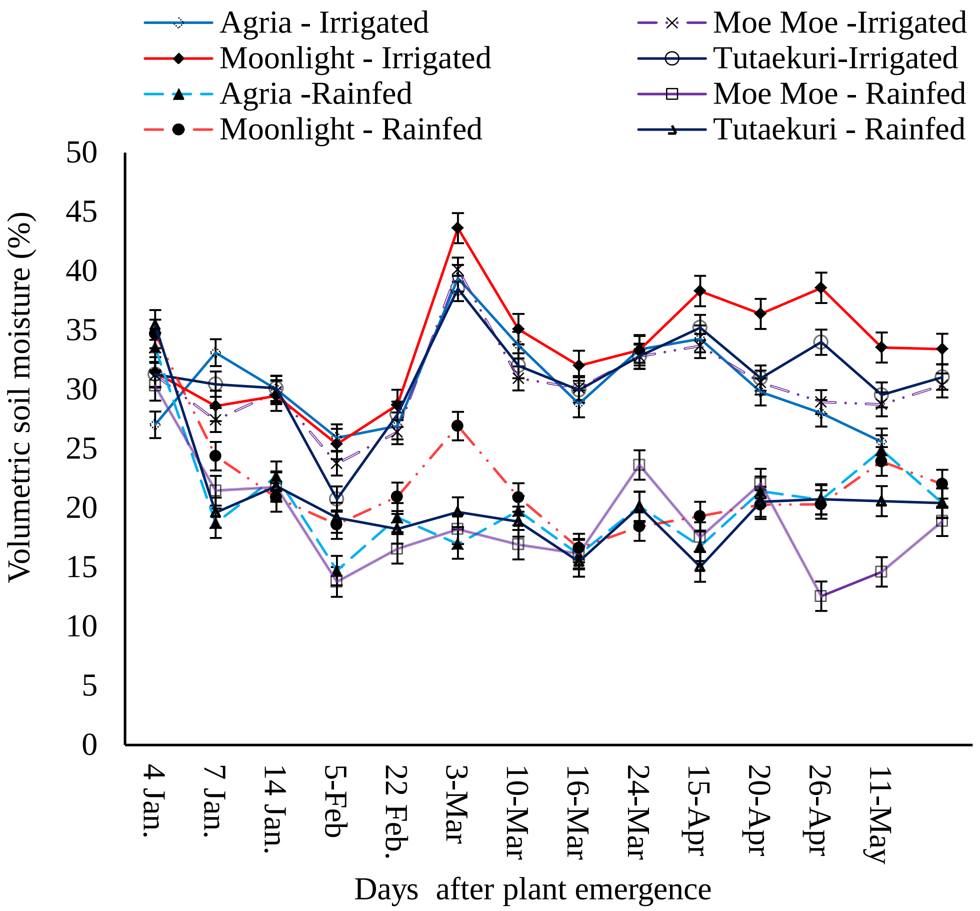


Figure 4.1.2 Volumetric soil moisture (%) change in Taewa and modern potato under irrigation and rain-fed conditions. Error bar represents ±SEM.

4.3.1.3.2 Vegetative growth characteristics of Taewa and modern potato cultivars

4.3.1.3.2.1 Flower production and physiological maturity

Cultivars and irrigation did not statistically affect flowering (P>0.05; Table 4.1.1). Taewa and modern potatoes matured after 132 and 179 days from planting, respectively.

Table 4.1.1 Vegetative growth and yield component characteristics of Taewa and modern potato cultivars under irrigation and rain-fed conditions in 2010. Measured at harvest except days to flowering.

Water regime/ Cultivars	Days to flowering	Plant height (cm)	Stems per plant	Branches /plant	Stem Diameter (mm)
Irrigation (n=8)					
Agria	62	44.4	2.7	0.7	12.5
Moonlight	55	54.4	2.1	6.1	13.8
Moe Moe	54	85.9	1.7	13.4	15.2
Tutaekuri	57	80.5	1.5	11.4	17.5
Mean(n=16)	57	66.3	2.0	7.9	14.8
Rain-fed (n=8)					
Agria	62	40.9	3.0	1.0	12.9
Moonlight	56	46.1	3.0	3.1	12.2
Moe Moe	53	84.1	2.3	15.1	17.1
Tutaekuri	58	78.3	1.7	12.7	14.4
Mean (n= 16)	57	59.9	2.5	8.0	14.1
Sign.					
Cultivars	Ns	P<0.0001	P<0.05	P<0.0001	P<0.05
Water regime	Ns	P<0.05	Ns	Ns	Ns
$LSD_{0.05}$					
Cultivars	-	6.81	0.85	1.91	3.2
Water regime	-	4.81	-	-	-

4.3.1.3.2.2 Average plant height (cm) and number of main stems and branches per plant and Stem diameter (mm)

Taewa cultivars were the tallest, whilst the modern cultivars were the shortest cultivars (P<0.0001; Table 4.1.1). Moe Moe was the tallest cultivar but similar to Tutaekuri. Moonlight was intermediate in height, whereas Agria was the shortest. Irrigated crops were significantly taller than rain-fed crops (P<0.05). Moe Moe did not show a reduction in its height, following a water deficit, whilst the two modern cultivars had significantly reduced height, due to water stress (P<0.05). Stems and branch aggregates per plant were not influenced by irrigation: they were influenced by type of cultivar (P<0.05, P<0.001). Moonlight had the largest average number of stems per plant, the same as Agria (P<0.05). Agria and Moonlight had more main stems and fewer branches per plant than the Taewa cultivars. The number of branches on Taewa was twice that for

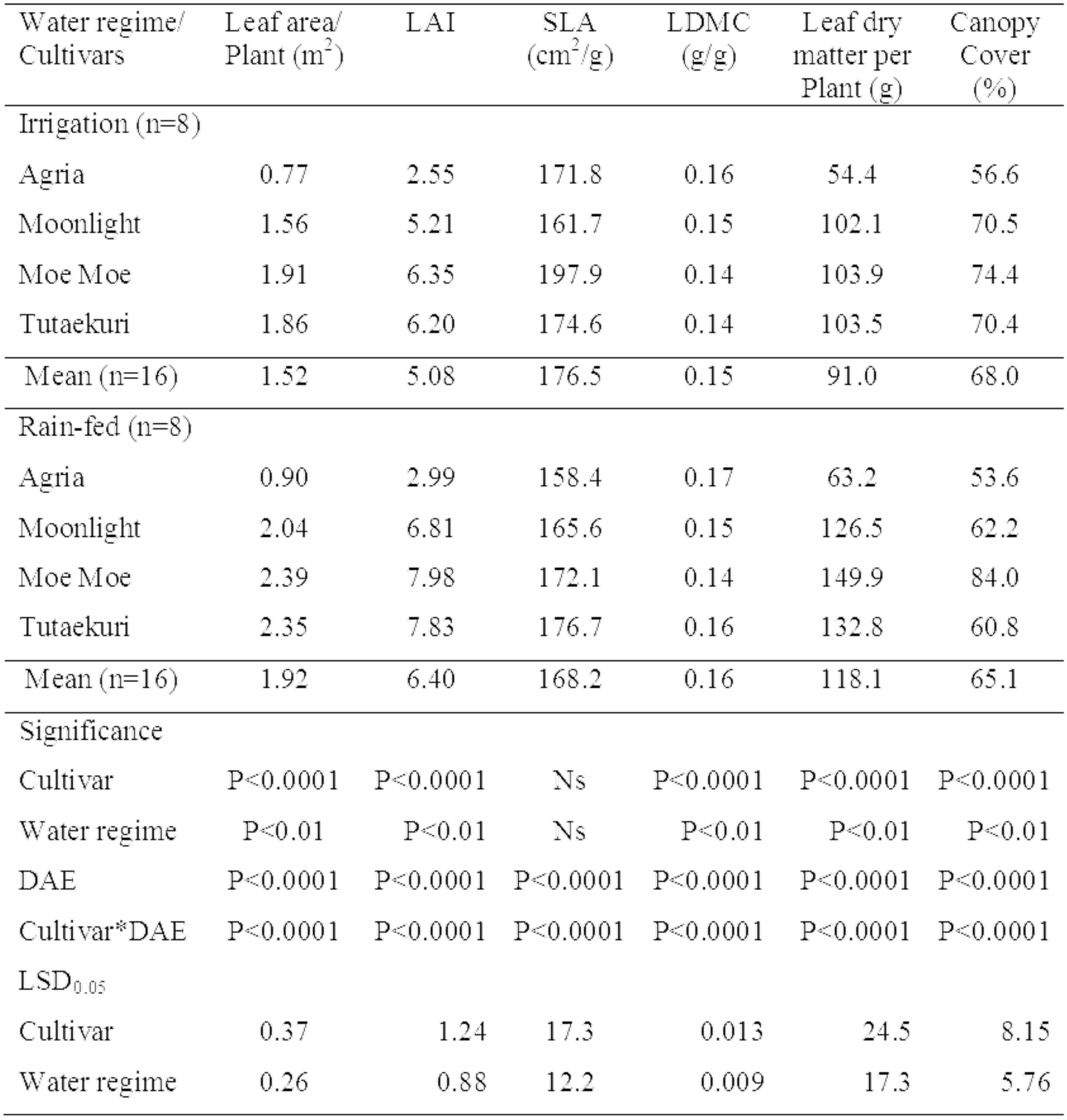
Moonlight: and more than ten times that for Agria (Table 4.1.1). Taewa had the largest stem diameter whilst the modern cultivars had the smallest diameter, especially Agria ($P<0.05$, Table 4.1.1). Irrigation had no significant effect on stem diameter ($P>0.05$) (Table 4.1.1).

4.3.1.3.2.3 Leaf characteristics

Leaf area index, leaf dry matter per plant (g), LDMC (g g^{-1}), and crop canopy (%), differed between potato cultivars and DAE ($P<0.0001$; Table 4.1.2). Irrigation had an effect on LAI, leaf dry matter per plant, canopy cover and LDMC (g/g) ($P<0.01$), but not on SLA (cm^2 g^{-1}) ($P>0.05$). Specific leaf area varied with time of plant growth ($P<0.0001$), but not with cultivar and irrigation ($P>0.05$). On average, Taewa cultivars were highest in these leaf features, except for LDMC ($P<0.0001$). Agria was the smallest value for these traits, except for LDMC, where it was the highest. Moonlight was intermediate in these traits ($P<0.0001$; Table 4.1.2). There were significant interactions between cultivar and DAE on leaf area, LAI, SLA, LDMC, leaf dry matter per plant and canopy cover ($P<0.0001$).

The leaf trait above increased from emergence and they reached a peak almost at the same time for all cultivars, prior to their senescence after 95 DAE ($P<0.0001$; Table 4.1.2). It was observed that the crop canopy was mainly affected by cultivars, not the water regime, although the highest was rain-fed Moe Moe, followed by irrigated Moe Moe and Tutaekuri ($P<0.0001$). Moonlight produced the highest canopy at the end, due to its delayed senescence, whilst the canopy decline in Agria was very drastic. Unlike the leaf area and canopy cover, the LDMC and SLA increased at an increasing rate until senescence, when it was highest in Tutaekuri and Moe Moe, respectively.

Table 4.1.2 Average leaf features of Taewa and modern potato cultivars under irrigation and rain-fed condition, 2009/2010



Water regime/ Cultivars	Leaf area/ Plant (m^2)	LAI	SLA (cm^2/g)	LDMC (g/g)	Leaf dry matter per Plant (g)	Canopy Cover (%)
Irrigation (n=8)						
Agria	0.77	2.55	171.8	0.16	54.4	56.6
Moonlight	1.56	5.21	161.7	0.15	102.1	70.5
Moe Moe	1.91	6.35	197.9	0.14	103.9	74.4
Tutaekuri	1.86	6.20	174.6	0.14	103.5	70.4
Mean (n=16)	1.52	5.08	176.5	0.15	91.0	68.0
Rain-fed (n=8)						
Agria	0.90	2.99	158.4	0.17	63.2	53.6
Moonlight	2.04	6.81	165.6	0.15	126.5	62.2
Moe Moe	2.39	7.98	172.1	0.14	149.9	84.0
Tutaekuri	2.35	7.83	176.7	0.16	132.8	60.8
Mean (n=16)	1.92	6.40	168.2	0.16	118.1	65.1
Significance						
Cultivar	$P<0.0001$	$P<0.0001$	Ns	$P<0.0001$	$P<0.0001$	$P<0.0001$
Water regime	$P<0.01$	$P<0.01$	Ns	$P<0.01$	$P<0.01$	$P<0.01$
DAE	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$
Cultivar*DAE	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$
$LSD_{0.05}$						
Cultivar	0.37	1.24	17.3	0.013	24.5	8.15
Water regime	0.26	0.88	12.2	0.009	17.3	5.76

4.3.1.3.3 Photosynthetic water use efficiency and gaseous exchange

4.3.1.3.3.1 Photosynthetic water use efficiency (µmolCO_2/m molH_2O)

Photosynthetic WUE (µmolCO_2/m molH_2O) significantly varied between water regimes ($P<0.0001$) and cultivars ($P<0.001$) and between measurement days ($P<0.0001$, Table 4.1.3, Appendix 4.4.4). On average, Agria had the highest photosynthetic WUE, similar to Moe Moe (Appendix 4.4.4). Photosynthetic WUE was significantly high under irrigation (Appendix 4.4.4, $P<0.05$). Photosynthetic WUE was lowest at Day 21 and it then increased to Day 48, followed by a decrease ($P<0.0001$; Appendix 4.4.4). Moe Moe had the highest photosynthetic WUE under rain-fed, at Day 48 (Appendix 4.4.4).

Table 4.1.3 Gaseous exchange in Taewa and modern potato cultivars under different water regimes under field conditions, 2009/2010

Cultivars/Water regime/ DAE	Photosynthetic WUE (μmolCO_2/m molH_2O)	Net Photosynthesis (μmolCO_2 m^2s^{-1})	Stomatal Conductance (mmolCO_2 m^2s^{-1})	Transpiration rate (mmolH_2O m^2s^{-1})	Internal Carbon (ppm)	Vapour pressure deficit
Cultivars (n=8)						
Agria	7.3^{a}	21.8^{a}	620.9	3.2	307.0	7.5
Moonlight	6.5^{b}	19.1^{b}	663.8	3.2	307.8	6.8
Moe Moe	7.2^{a}	21.6^{a}	660.5	3.3	317.7	6.2
Tutaekuri	6.8^{b}	19.4^{b}	658.3	3.1	299.7	6.2
Significance	$P<0.001$	$P<0.0001$	Ns	Ns	Ns	Ns
Water regime (n=16)						
Irrigation	7.9^{a}	20.5^{a}	687.5	3.2	294.2^{b}	6.6
Rain-fed	5.9^{b}	14.4^{b}	616.2	3.1	321.9^{a}	6.8
Significance	$P<0.0001$	$P<0.0001$	Ns	Ns	$P<0.0001$	Ns
Days after emergence (n=32)						
21	4.6^{c}	15.2^{c}	637.4^{b}	3.5^{a}	350.2^{a}	7.4^{ba}
48	9.8^{a}	24.8^{a}	753.4^{a}	2.6^{b}	286.4^{b}	4.3^{c}
64	6.8^{b}	21.5^{b}	584.4^{b}	3.3^{a}	298.2^{b}	8.1^{a}
90	6.4^{b}	20.4^{b}	632.1^{b}	3.3^{a}	297.4^{a}	6.9^{b}
Sign.	$P<0.0001$	$P<0.0001$	$P<0.01$	$P<0.01$	$P<0.05$	$P<0.0001$

4.3.1.3.3.2 Net photosynthesis (µmolCO$_2$ m^2 s^{-1}) of four potato cultivars

Net photosynthesis (A_n) significantly varied between potato cultivars, water regimes and DAE ($P<0.0001$, Table 4.1.3, Appendix 4.4.4). Appendix 4.4.4 shows that Agria and Moe Moe had the highest A_n under irrigation and rain-fed conditions, respectively. The average seasonal A_n for the two cultivars did not vary ($P>0.05$). There was a consistent pattern of increasing and then decreasing A_n from early to later measurements ($P<0.0001$; Table 4.1.3). Net photosynthesis was greatest on Day 48 in both irrigated and rain-fed potato (Appendix 4.4.4; Table 4.1.3).

4.3.1.3.3.3 Stomatal conductance (m molCO$_2$ m2 s-1) and transpiration rate (m molH$_2$O m^{2}s^{-1})

The g_s and T only differed between measurement days, with the highest g_s and lowest T on Day 48 in Moonlight ($P<0.01$, Table 4.1.3). Potato cultivars and irrigation had no significant effect on g_s and T ($P>0.05$).

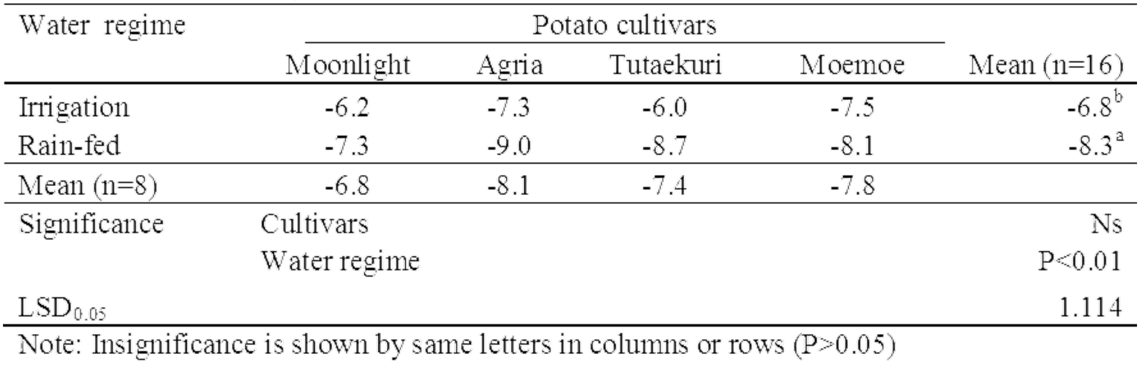
4.3.1.3.3.4 Internal CO$_2$ concentration and vapour pressure deficits

Internal CO$_2$ concentration was highest on Day 21 and lowest at Day 48 ($P<0.0001$), with no statistical differences between cultivars ($P>0.05$), but there was a difference between water regimes ($P<0.0001$). Irrigation significantly reduced Ci, whilst VPD only differed between DAE ($P<0.0001$) and not between cultivars and irrigation ($P>0.05$; Table 4.1.3).

4.3.1.3.4 Leaf water potential (Ψ_w)

Leaf water potential (**Ψ_w**) was significantly influenced by the water regime ($P<0.01$) and not by cultivars ($P>0.05$; Table 4.1.4). The rain-fed plants had the lowest leaf water potential, compared to the irrigated plants. The potato cultivars were similar ($P>0.05$).

Table 4.1.4 Effect of water regimes on leaf water potential (bars) in four potato cultivars, 2009/2010



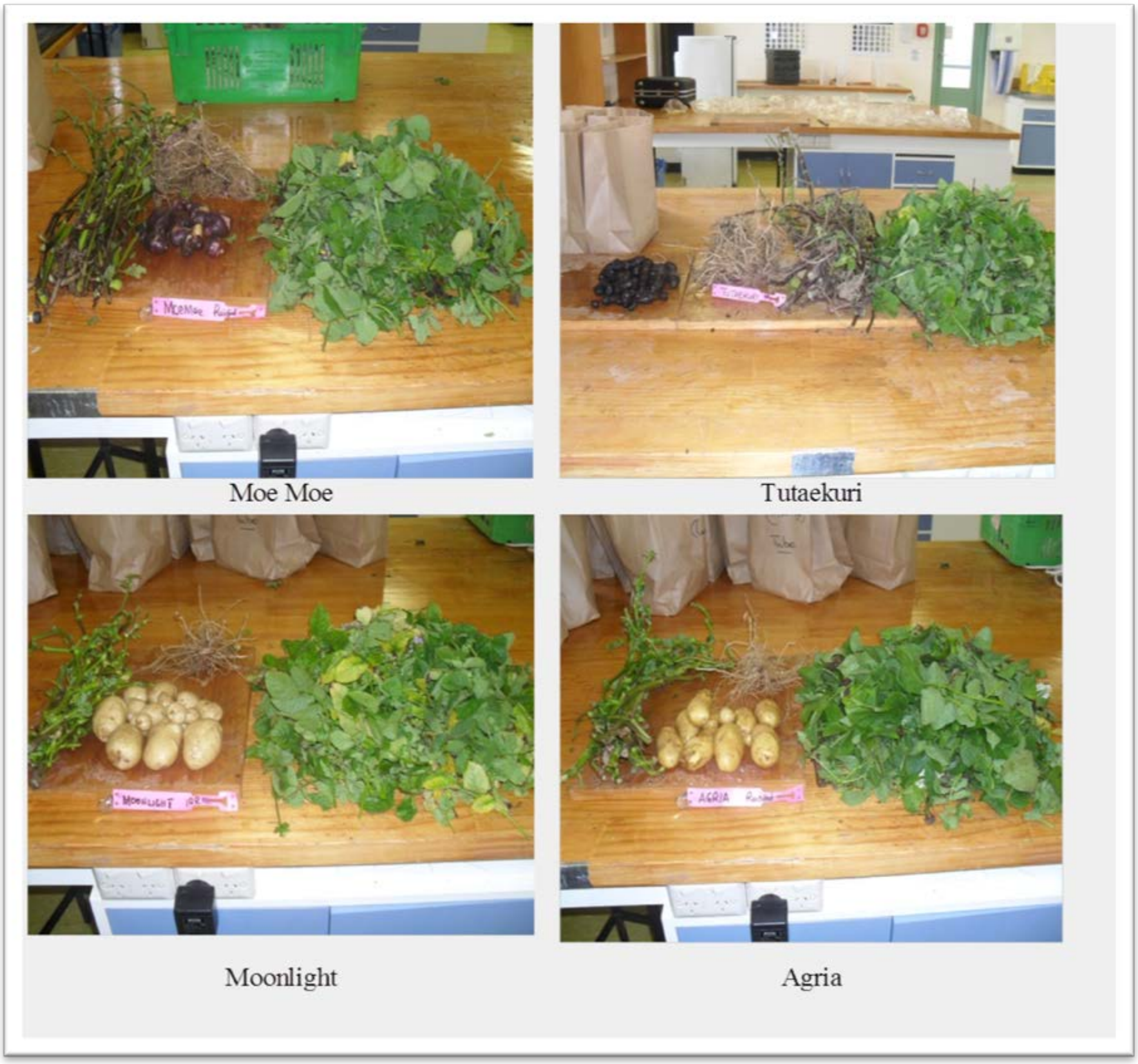
Water regime	Potato cultivars				
	Moonlight	Agria	Tutaekuri	Moemoe	Mean (n=16)
Irrigation	-6.2	-7.3	-6.0	-7.5	-6.8^b
Rain-fed	-7.3	-9.0	-8.7	-8.1	-8.3^a
Mean (n=8)	-6.8	-8.1	-7.4	-7.8	
Significance	Cultivars				Ns
	Water regime				P<0.01
$LSD_{0.05}$					1.114

Note: Insignificance is shown by same letters in columns or rows (P>0.05)

4.3.1.3.5 Dry matter production and partitioning characteristics

The average total dry matter production per plant measured 100 days after planting was not significantly different between potato cultivars and irrigation (P>0.05; Table 4.1.5, Plate 4.2). However, on partitioning of these plants into leaves, stems, roots and tubers, statistical differences emerged between cultivars (P<0.05). Irrigation had no significant effect on dry matter partitioning into leaves, stems and tubers (P>0.05), except partitioning to the roots (P<0.05), (Table 4.1.5, Appendix 4.4.5, Plate 4.2). Water stressed potato had highest root dry matter and root: shoot ratio was highest for Taewa (P<0.05).

Taewa had more biomass in leaves, stems and roots, whilst modern cultivars had more tuber biomass per plant. Tutaekuri allocated >37% to leaves, >36% to stems and >8% of its biomass to roots, compared to Agria which translocated >60% to tubers and the least to leaves, stems and roots (P<0.0001) (Appendix 4.4.5; Table 4.1.5). The trend of allocating assimilates in Moe Moe was followed by Tutaekuri, although it was not statistically different, whilst Moonlight was intermediate. Agria and Moonlight significantly partitioned differently in stems and tubers, but not in leaves and roots (Table 4.1.5, Appendix Table 4.4.5).



Moe Moe

Tutaekuri

Moonlight

Agria

Plate 4.2 : A sample of fresh biomass partitioning per plant into leaves, stems, tubers and roots in two Taewa and two modern potato cultivars (2009/2010)

Table 4.1.5 Effect of water regimes on amount of leaves, stems, roots, tubers and total biomass on dry matter basis per plant (g) measured 100 days after planting, in four potato cultivars, 2009/2010

Water Regime/	Dry matter production & partitioning per plant (g)					Root : Shoot ratio	HI (%)
Cultivars	Leaf	Stem	Roots	Tuber	Total biomass		
Irrigation (n=8)							
Agria	74.3	44.5	8.8	274.9	402.5	0.07	68
Moonlight	90.3	51.5	11.6	177.0	330.4	0.08	54
Moe Moe	113.6	109.5	21.9	116.7	361.8	0.10	32
Tutaekuri	145.2	173.0	30.1	103.3	451.7	0.09	23
Mean (n=16)	105.9	94.6	18.1	168.0	386.6	0.08	44
Rain-fed (n=8)							
Agria	86.8	39.5	9.5	208.9	344.7	0.08	61
Moonlight	147.3	89.2	17.8	175.9	430.3	0.08	41
Moe Moe	135.9	125.1	36.0	138.7	435.7	0.14	32
Tutaekuri	176.2	150.2	41.5	71.7	439.6	0.13	16
Mean (n=16)	136.6	101.0	26.2	148.8	412.6	0.11	37
Significance							
Cultivars	$P<0.05$	$P<0.0001$	$P<0.0001$	$P<0.01$	Ns	$P<0.05$	$P<0.05$
Water regime	Ns	Ns	$P<0.05$	Ns	Ns	$P<0.05$	Ns
$LSD_{0.05}$							
Cultivars	47.4	32.6	8.5	76.6	-	0.02	9.1
Water regime	33.5	23.0	6.0	54.2	-	0.01	7.0

4.3.1.3.6 Tuber yield and yield components in Taewa and modern potato cultivars

There were significant differences between irrigation and rain-fed potatoes on average tuber weight ($P<0.001$), total tuber yield ($P<0.0001$) and marketable tuber yield ($P<0.01$; Table 4.1.6). However, there was no difference between the number of tubers per plant and HI ($P>0.05$), between irrigation and rain-fed potatoes. Irrigation enhanced the average tuber weight; fresh total tuber yield; and marketable tuber yield, by 51%, 33% and 55%, respectively (Table 4.1.6). Potato cultivars strongly influenced the number of tubers per plant; average tuber weight ($P<0.0001$); total tuber weight ($P<0.0001$); and marketable tuber yield ($P<0.0001$) and HI ($P<0.0001$) (Table 4.1.6).

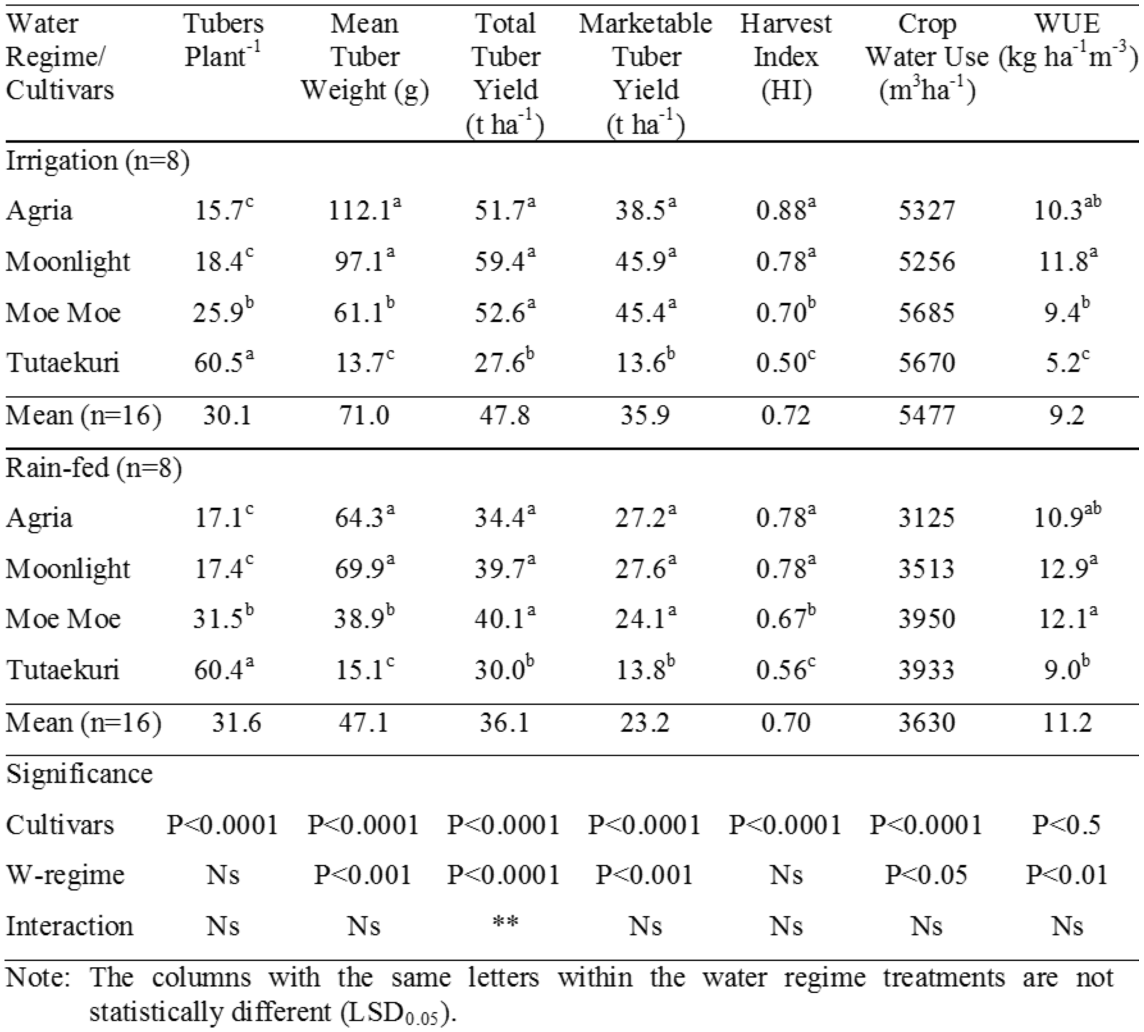
The highest number of tubers per plant was found in Tutaekuri and modern cultivars had the least, whilst Moe Moe was intermediate. Unlike the other two potato cultivars, Moe Moe and Agria had more tubers under rain-fed conditions. The average tuber weight for modern potato cultivars were 1.7 times that of Moe Moe and almost 5.9 times that of Tutaekuri. The greatest average tuber weight was found in Agria, whilst Tutaekuri was the least. Modern cultivars did not differ in the number of tubers per plant and average tuber weight traits, whilst Taewa cultivars differed from each other ($P<0.0001$; Table 4.1.6).

The water regime did not affect the number of tubers per plant in Agria and Moonlight: and neither did it affect both the number of tubers and the average tuber weight in Tutaekuri ($P>0.05$). Conversely, the number of tubers per plant in Moe Moe were reduced and there was an increase in the mean tuber weight with irrigation ($P<0.001$). Subsequently, the total fresh tuber yields and marketable tuber yields were not significantly different between Agria, Moonlight and Moe Moe, but they were all different to the lowest yielding, Tutaekuri, under both environments ($P<0.0001$). The tuber yields for Agria, Moonlight and Moe Moe were almost double that of Tutaekuri. The total fresh tuber yields and marketable tuber yields, for Tutaekuri, were not influenced by the water regime ($P>0.05$; Table 4.1.6).

The behaviour of translocating assimilates to the harvested product was clearly demonstrated (by the highest HI after 100 days from planting and at harvest) in Agria. Tutaekuri had the lowest HI whilst Moe Moe was intermediate (Table 4.1.5, Table 4.1.6). The HI confirms that Taewa partitioned more dry matter to above-ground, whilst the modern cultivars partitioned more dry matter to tubers, as presented in Table 4.1.5, and Table 4.1.6.

The water regime and cultivar interaction effects were observed on total tuber yield ($P<0.01$; Fig. 4.1.3). This interaction shows that irrigation increased total tuber yields in Agria, Moonlight and Moe Moe, but not in Tutaekuri. The effect of water stress was highly pronounced in Agria and Moonlight, whilst Moe Moe and Tutaekuri were somehow resistant to total yield reduction, as a result of water stress (Fig. 4.1.3).

Table 4.1.6 Yield and yield components for Taewa and modern potato cultivars under irrigation and rain-fed conditions, 2009/2010



Water Regime/ Cultivars	Tubers Plant^{-1}	Mean Tuber Weight (g)	Total Tuber Yield (t ha^{-1})	Marketable Tuber Yield (t ha^{-1})	Harvest Index (HI)	Crop Water Use (m^{3}ha^{-1})	WUE (kg ha^{-1}m^{-3})
Irrigation (n=8)							
Agria	15.7^{c}	112.1^{a}	51.7^{a}	38.5^{a}	0.88^{a}	5327	10.3^{ab}
Moonlight	18.4^{c}	97.1^{a}	59.4^{a}	45.9^{a}	0.78^{a}	5256	11.8^{a}
Moe Moe	25.9^{b}	61.1^{b}	52.6^{a}	45.4^{a}	0.70^{b}	5685	9.4^{b}
Tutaekuri	60.5^{a}	13.7^{c}	27.6^{b}	13.6^{b}	0.50^{c}	5670	5.2^{c}
Mean (n=16)	30.1	71.0	47.8	35.9	0.72	5477	9.2
Rain-fed (n=8)							
Agria	17.1^{c}	64.3^{a}	34.4^{a}	27.2^{a}	0.78^{a}	3125	10.9^{ab}
Moonlight	17.4^{c}	69.9^{a}	39.7^{a}	27.6^{a}	0.78^{a}	3513	12.9^{a}
Moe Moe	31.5^{b}	38.9^{b}	40.1^{a}	24.1^{a}	0.67^{b}	3950	12.1^{a}
Tutaekuri	60.4^{a}	15.1^{c}	30.0^{b}	13.8^{b}	0.56^{c}	3933	9.0^{b}
Mean (n=16)	31.6	47.1	36.1	23.2	0.70	3630	11.2
Significance							
Cultivars	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.5$
W-regime	Ns	$P<0.001$	$P<0.0001$	$P<0.001$	Ns	$P<0.05$	$P<0.01$
Interaction	Ns	Ns	**	Ns	Ns	Ns	Ns

Note: The columns with the same letters within the water regime treatments are not statistically different ($LSD_{0.05}$).

There was also a significant relationship between the number of tubers and the average tuber weight and HI at harvest. The number of tubers per plant were negatively related to average tuber weight (Average tuber weight (g) = - 1.6618 (Tubers plant^{-1}) + 110.29, R^2 = 66.3%) and harvest index (HI = - 0.0059 (Tubers plant^{-1}) + 0.8902, R^2 = 60.5%). The increase in the number of tubers per plant significantly decreased the average tuber weight and HI (Appendix 4.4.6). The average tuber weight was also negatively related to plant height (r = - 0.52, $P<0.01$); number of branches per plant (r - = 0.60, $P<0.01$); stem diameter (r = - 0.32, $P<0.05$); and total fresh biomass per plant (r = - 0.63, $P<0.001$). In this case, Taewa's vegetative growth and yield characteristics were related to a reduced average tuber weight in potato (Appendix 4.4.6).

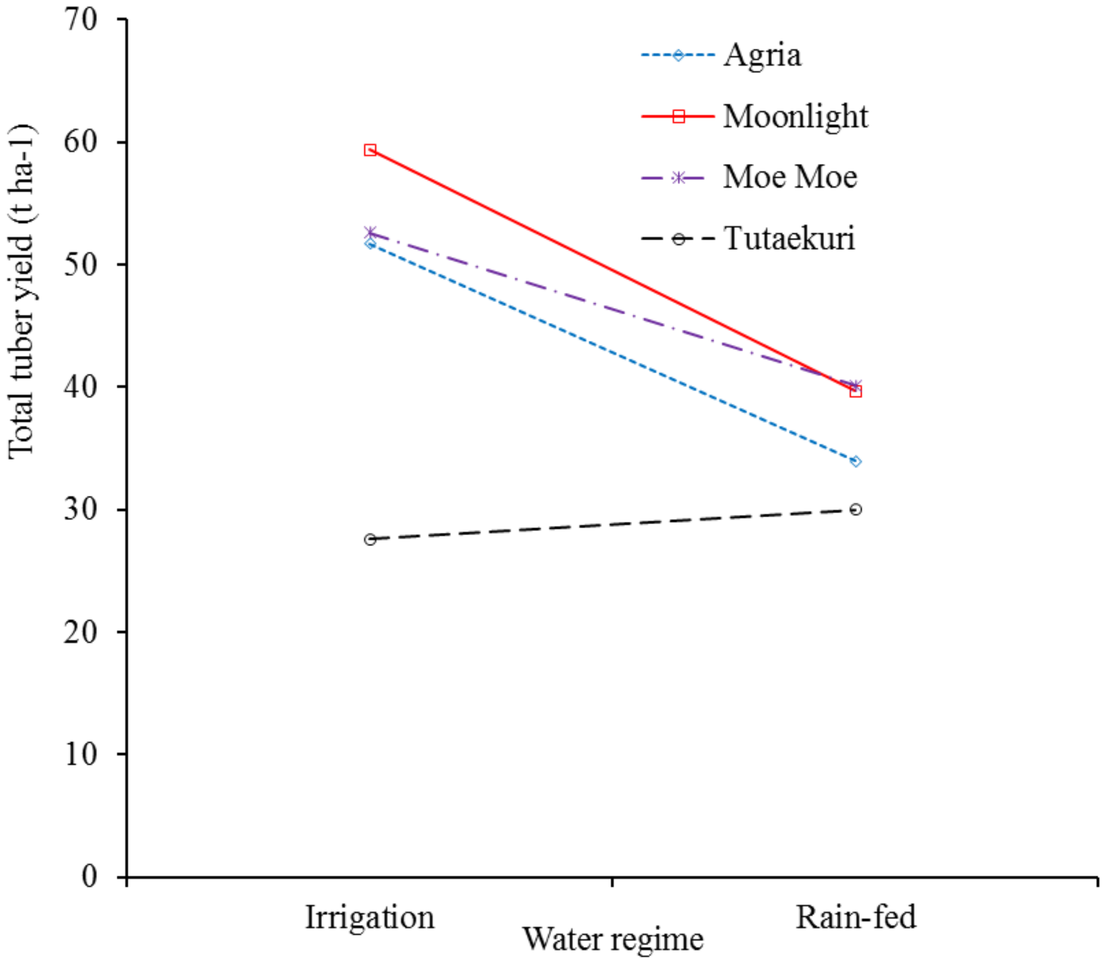


Figure 4.1.3 Interaction between cultivars and water regime on total tuber yield (t ha^{-1}).

4.3.1.3.7 Water use efficiency for Taewa and modern potato cultivars

Water use efficiency of total tuber yield was significantly influenced by the water regime and cultivars ($P<0.01$; $P<0.05$; Table 4.1.6). Rain-fed potato had high WUE. On average, Moonlight had the highest average WUE, although it was not significantly different from Moe Moe and Agria: but it was different from Tutaekuri ($P<0.05$). Tutaekuri did not differ from Agria in WUE under rain-fed regime. In addition, Moonlight did not differ from Moe Moe in WUE under rain-fed, but it did differ under irrigated conditions, with the highest being found in Moonlight (Table 4.1.6).

4.3.1.3.8 Specific gravity, tuber dry matter content and total sugars

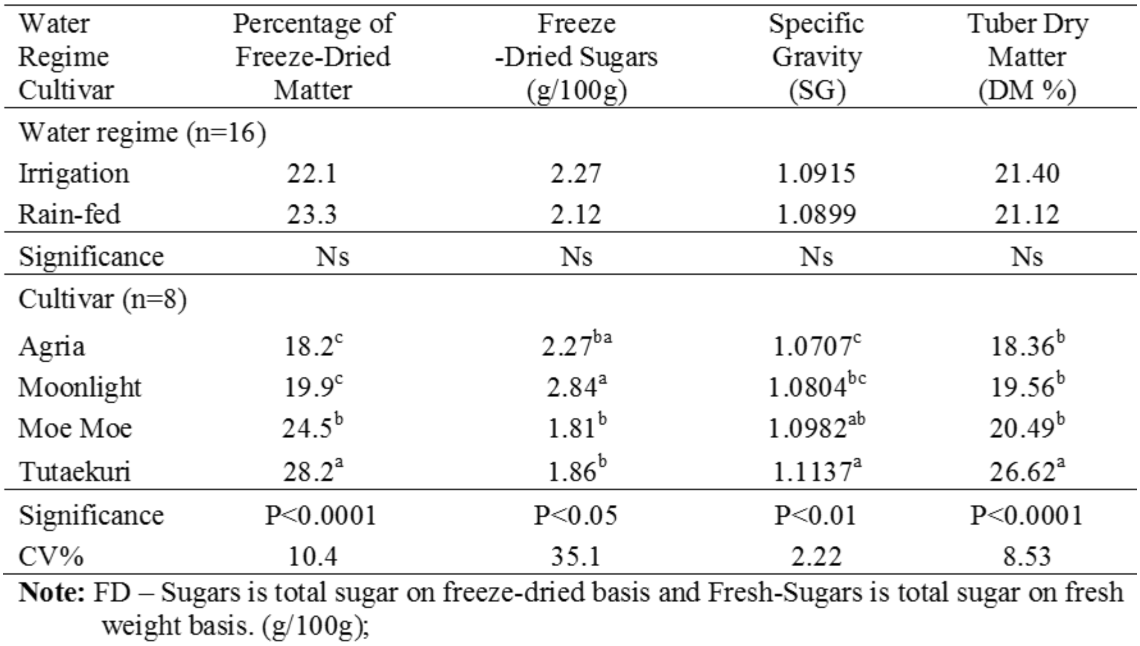
Specific gravity and DM (%) were significantly different between cultivars ($P>0.01$, $P<0.0001$) but not between water regimes ($P>0.05$; Table 4.1.7). Tutaekuri had the highest SG and tuber DM (%), whilst Agria had the lowest SG and DM (%). Tutaekuri was significantly different from all the cultivars in SG and DM%, whilst Agria and Moonlight were least in all traits. Moe Moe was intermediate in SG traits (Table 4.1.7).

Specific gravity, within the four potato cultivars, was highly and positively correlated with the tuber dry matter content, DM (%) = 49.329 (SG) - 32.548, $R^2 = 0.21$, ($P<0.01$) and percentage freeze-dried matter, percentage FDM = 53.043 (SG) - 35.16, $R^2 = 0.16$, $P<0.05$ (Fig. 4.3.6). Potato cultivars with high SG and thus, Taewa had increased DM % (Table 4.1.7 and Appendix 4.4.7a).

Total sugars on freeze-dried matter basis and percentage of freeze-dried matter significantly differed between potato cultivars ($P<0.01$, $P<0.0001$), but not between water regimes ($P<0.05$; Table 4.1.8). Moonlight had the highest total sugars, although it was not significantly different from Agria. However, they were both different from Moe Moe and Tutaekuri, which were least but not statistically different to Agria. Tutaekuri had a significant highest percentage freeze-dried matter content, which was different from all the potato cultivars, whilst Agria was similar to Moonlight. Moe Moe had an intermediate percentage freeze-dried matter amongst the four potato cultivars (Table 4.1.7).

The total sugars on a freeze-dried matter basis negatively related to the percentage of freeze-dried matter or dry matter content (%), ($P<0.05$) and DM at harvest: but not to SG ($P>0.05$). However, the increase of both DM and SG decreased the total sugar content (Appendix 4.4.7b). The equations for total sugars' relationship with DM are: total sugars = - 0.0818(%FDM) + 4.05, $R^2 = 20$; total sugars = - 0.0806 (DM %) + 3.91, $R^2 = 0.13$, whilst the equation for total sugars to specific gravity is total sugars= - 6.2185 (SG) + 8.9786, $R^2 = 0.07$, as presented in appendix 4.4.7b. The cultivars with high total sugars (that is modern cultivars) had low DM (%) and SG (Table 4.1.7 and appendix 4.4.7).

Table 4.1.7 Effect of water regime and cultivars on total sugars, percentage of freeze-dried matter, specific gravity and dry matter content, in 2009/2010 growing season



Water Regime Cultivar	Percentage of Freeze-Dried Matter	Freeze -Dried Sugars (g/100g)	Specific Gravity (SG)	Tuber Dry Matter (DM %)
Water regime (n=16)				
Irrigation	22.1	2.27	1.0915	21.40
Rain-fed	23.3	2.12	1.0899	21.12
Significance	Ns	Ns	Ns	Ns
Cultivar (n=8)				
Agria	18.2^{c}	2.27^{ba}	1.0707^{c}	18.36^{b}
Moonlight	19.9^{c}	2.84^{a}	1.0804^{bc}	19.56^{b}
Moe Moe	24.5^{b}	1.81^{b}	1.0982^{ab}	20.49^{b}
Tutaekuri	28.2^{a}	1.86^{b}	1.1137^{a}	26.62^{a}
Significance	$P<0.0001$	$P<0.05$	$P<0.01$	$P<0.0001$
CV%	10.4	35.1	2.22	8.53

Note: FD – Sugars is total sugar on freeze-dried basis and Fresh-Sugars is total sugar on fresh weight basis. (g/100g);

4.3.1.4 Discussion

4.3.1.4.1 Vegetative growth characteristics

Taewa had more vegetative growth supported by few main tall stems with many branches, leaf area and large canopy, compared to modern potato cultivars. A similar trend has been observed in old wheat (Siddique *et al.,* 1989). The increase in the number of leaves, leaf size and branches in Taewa could be associated with high radiation utilisation. On the other hand, the leaf features indicate that high vegetative growth in Taewa was accompanied by low LDMC, compared to modern cultivars. Wilson *et al.,* (1999) studied LDMC and SLA and reported that LDMC is a more accurate predictor of how resources are captured and used in plants for growth. In the case of this study, modern cultivars appear to be able to efficiently utilise radiation resources, compared to Taewa. Siddique *et al.* (1989) found modern wheat cultivars to be more efficient in capturing radiation than old cultivars, despite large LAI. The high vegetative growth in old cultivars caused mutual shading and a high humid micro-climate, which resulted in low radiation use and low LDMC (Siddique *et al.*, 1989).

In both Taewa and modern cultivars, irrigation played a role in increasing leaf features, plant height and the partitioning to the roots, but not on the number of stems and branches per plant. Outstandingly, the overall vegetative growth characteristics were greatly influenced by cultivar differences (Jefferies *et al.*, 1993ab). Taewa, despite early flowering (in comparison with the modern cultivar, Agria), was the latest to mature regardless of irrigation. The possible reason for this observation is that Taewa is not bred for early maturity comparable to modern cultivars. Early flowering in Taewa is part of their survival strategy (for seed production of the next generation) developed during self-selection (Roskruge *et al.* 2010). This was also observed in the glasshouse (see Chapter 3). Nevertheless, adequate water was essential for canopy development, whereas water stress encouraged deep rooting, as observed in Taewa. It has been reported that dry matter is associated with LAI (Jefferies *et al.*, 1993b) and therefore reduction in leaf features by water deficit decreases production, whilst it increases assimilation to the roots as an adaptation strategy to water stress, as reported by Liu *et al.* (2006b).

4.3.1.4.2 Photosynthetic WUE and gaseous exchange of Taewa and modern potato

The field experiment in 2009/2010 persistently found photosynthetic WUE and A_n being influenced by cultivars, irrigation and DAE, as also observed in the glasshouse (Chapter 3) and other studies (Ghosh *et al.*, 2000; Vos *et al.*, 1989a; Vos *et al.*, 1987). Contrary to the glasshouse and Ghosh's findings (2000), the highest photosynthetic WUE and A_n in this study was on 48DAE, in both Taewa and modern cultivars. This photosynthetic WUE trend still reflected A_n and it declined with age (Ahmadi *et al.*, 2010; Ghosh *et al.*, 2000). The seasonal photosynthetic WUE and A_n increased up to day 48 before declining with time, regardless of irrigation and cultivars, with the lowest on day 21 (see Appendix 4.4.3). This suggests that the period of tuberisation, the likely cause of high A_n (Moorby, 1970), is not static at 21 DAE, as observed in the glasshouse and reported by Ghosh *et al.* (2000), but it ranges from three weeks to seven weeks from plant emergence.

Moe Moe had an extended highest photosynthetic WUE under irrigation, apart from the highest photosynthetic WUE and A_n under rain-fed conditions. Despite this finding, the average photosynthetic WUE and A_n, for Moe Moe and Agria, were comparable and this was also found in Tutaekuri and Moonlight (Table 4.1.3). The high photosynthetic WUE characteristics of Moe Moe under rain-fed and the increased A_n and low Ci with irrigation indicate that increased water stress, during a drought year, may steadily affect gaseous exchange in modern cultivars, unlike that seen in Tutaekuri. This shows that the ability to adapt to low water supply, as observed in the glasshouse (see Chapter 3) and reported in old wheat cultivars (Koç *et al.*, 2003), exists in Taewa.

Generally, these findings confirm that A_n and photosynthetic WUE in potato are limited by water deficit (Ahmadi *et al.*, 2010; Olesinski *et al.*, 1989). Schapendonk *et al.* (1989) reported potato genotypic variation in A_n under well watered and limited water. However, the response to water deficit was primary regulated by stomatal closure followed by mesophyllic activity when water stress was severe, as also observed in most C3 plants (Flexas *et al.*, 2002). The Ci for rain-fed treatment in this study increased, thus signifying severe water stress to have fully induced A_n and photosynthetic WUE reduction. This is factual, because Ci is greatly affected by mesophyllic activity (Schapendonk *et al.*, 1989) and it is inversely related to A_n (Morison, 1998). However, the results of this study differs from Olensinski *et al.* (1989), who found that Ci was not affected by water deficit and this study also disagree with Liu's (2006a) report that photosynthetic WUE was higher under deficit irrigation than full irrigation. These results do not support suggestions that photosynthetic WUE is enhanced with restricted water use, possibly because A_n for rain-fed decreased, while g_s and T remained in the same range with the irrigated potato, which is contrary to other studies (Ahmadi *et al.*, 2010; Liu *et al.*, 2006a).

4.3.1.4.3 Leaf water potential of Taewa and modern potato cultivars

Water stress increased leaf water potential. However, the leaf water potential results did not demonstrate genotypic variability on leaf water potential, as reported in the Andean region between water regimes (Schafleitner *et al.*, 2007). The finding on leaf water potential confirms that potato leaf water potential is not as sensitive as gaseous exchange to water stress and hence it was not a very reliable indicator for cultivar tolerance to water stress, in 2009/2010 as formerly observed by Olesinski *et al.* (1989). The result suggested that leaf water potential was very reliable indicator of water stress between water regimes, rather than potato cultivars.

4.3.1.4.4 Dry matter partitioning and tuber yield of Taewa and modern potato

The results of the dry matter partitioning confirm that old cultivars translocate more dry matter to their leaves, stems and roots, whilst modern cultivars optimise partitioning to the harvested products (Ziska *et al.,* 2007). Genotypic variation in dry matter partitioning has been reported in four potato cultivars (Shepody, Frodo, Darius and Pentland Dell) by Geremew *et al.* (2007) and this has also been confirmed within Taewa and modern potato in this study. The substantial above-ground biomass and number of tubers per plant were responsible for the reduction of mean tuber weight and HI in Taewa. As the number of tubers per plant continued to increase in Tutaekuri, the mean tuber weight and HI deteriorated. This corresponds to Geremew's (2007) observation that the cultivar with the highest above-ground biomass (Shepody) has least translocation to tuber. It can be proposed that the large sink in Taewa affects tuber yields, due to diverse translocation of water and it assimilates at the expense of large tubers. However, these findings are unlike other studies (Jefferies *et al.,* 1993b; Geremew *et al.,* 2007), because it suggests that total dry matter production does not differ between cultivars (Taewa and modern cultivars), but instead they only differ on how each cultivar allocates assimilates to each component. Consequently, cultivars that priotise translocation of assimilates to tubers have high tuber yield.

The tuber yield results of this experiment substantiate and broaden other observations that irrigation improves potato yields (Erdem *et al.,* 2006) and also that there are potato genotypic differences in water use (Steyn *et al.,* 1998; Trebejo *et al.,* 1990; Wolfe *et al.,* 1983). The results clearly show that total and marketable tuber yields are strongly influenced by irrigation in both Taewa and modern potato cultivars, but not in Tutaekuri. Potato yields increased linearly with irrigation, depending on genotypes and the highest increase was found in modern potatoes. Evidently, the response to irrigation is high in cultivars that are very sensitive (or not tolerant) to water stress, which are predominantly modern cultivars. Interestingly; it is supported by the high reduction of modern potato cultivars with a mild water stress, as compared to Taewa. This congruently supports Trebejo's (1990) findings that cultivars which perform well under adequate water may not do well under water stress, unless the cultivar is stable to both a stressed and non-stressed environment, as observed with Moe Moe in this study.

Moe Moe (Taewa) is notable because it competitively produced equal tuber yields to modern cultivars. Moe Moe yield was also more than the average potato yield of 50.2 t ha^{-1} in New Zealand. It is also above the world potato average yields, which range from 10.8 to 41.2 t ha^{-1} (FAO, 2009). The performance of Moe Moe dispels claims which generalise that Taewa cultivars are 50% poorer in their yields than modern potato (Harris *et al.,* 1999). It also indicates the possibility of achieving high yields in some Taewa cultivars, if water is managed correctly. Moe Moe showed a good yield, regardless of its many branches, relative to modern cultivars. On the other hand, irrigation outstandingly failed to improve the tuber yield in one Taewa cultivar (Tutaekuri). Tutaekuri did not respond to irrigation like other cultivars, possibly due to differences in their sub-species and low HI. Tutaekuri is *Solanum tuberosum ssp. andigena,* whilst the other cultivars are *Solanum tuberosum ssp. tuberosum*. It is probable that a combination of irrigation with growth regulators, which have been reported to induce tuberisation in *S. tuberosum ssp. andigena* (Kumar *et al.,* 1973, 1974), could manoeuvre Tutaekuri to respond to irrigation, in a similar manner to other potato cultivars.

Irrigation enhances potato yields differently, through the modification of mean tuber weight and number of tubers per plant, depending on the cultivar (Belanger *et al.,* 2002; Walworth *et al.,* 2002). According to this study, irrigation almost doubled the mean tuber weight in all the high yielding potato cultivars (Agria, Moonlight and Moe Moe). However, the adjustment in Moe Moe was accompanied by a modification of the number of tubers per plant, which were fewer than those under rain-fed condition. Consequently, total and marketable tuber yields between Agria, Moonlight and Moe Moe were the same, regardless of the differences observed in the number of tubers and mean tuber weight. Moe Moe managed to compete with the modern cultivars (Agria and Moonlight) in achieving high yields, due to an intermediate number of tubers and mean tuber weight. The increase in mean tuber weight confirms other findings by Bélanger *et al.* (2002), Ferreira *et al.* (2007) and Yuan *et al.* (2003), whilst a decrease in the number of tubers with irrigation is contrary to Belanger *et al.* (2002) and Yuan *et al.* (2003), who reported an increase in tuber numbers per plant with irrigation.

The substantial vegetative growth and high number of tubers per plant were responsible for the reduction of total and marketable yields in Taewa (Roskruge *et al.,* 2010). The harvest index for Moe Moe and Tutaekuri was greatly affected by the large amount of vegetative growth. However, the increased number of tubers per plant in Tutaekuri increasingly deteriorated its tuber yield performance. These two traits increased the area for assimilates partitioning, at the expense of mean tuber weight improvement. Consequently, mean tuber weight was indifferent with irrigation in Tutaekuri, whilst Moe Moe increased mean tuber weight with irrigation and this instigated low total and marketable tuber yields in Tutaekuri. The yield component results depicts that the high number of tubers per plant heavily reduced the mean tuber weight and HI traits in the potato cultivars. This shows that Tutaekuri (as an old cultivar) has low yields, because it allocates more water and assimilates, in order to sustain vegetative growth and more yield components, at the expense of large tubers, as reported in wheat (Siddique *et al.*, 1990a), soyabean (Frederick *et al.*, 1991) and oat (Ziska *et al.*, 2007). Conversely, a high vegetative biomass will have an advantage over a modern cultivar, in response to the rise in CO_2 that will be caused by climate change, as observed in oats (Ziska *et al.*, 2007).

4.3.1.4.5 Water use efficiency

Moe Moe, a Taewa cultivar, had less or equal WUE to modern potato, whilst out performing Agria under water deficit conditions. As usual, the WUE for all cultivars was high under rain-fed (Zoebl, 2006). Moe Moe competed with modern potato cultivars in WUE and tuber yield, due to its tolerance to both a stressed and non-stressed water environment. This confirms that Moe Moe has a comparable capacity in tuber yield and WUE to modern cultivars, as observed in the glasshouse (see Chapter 3). This study confirms that WUE in potato is affected by genotype and agronomical water management practices (Bowen, 2003; Trebejo *et al.*, 1990). It is also notable that potato WUE for this study is within the global average, (except for Tutaekuri) which ranges from 6.2 kg m^{-3} to 11.6 kg m^{-3} (FAO, 2009).

Moe Moe had lower WUE under irrigation compared to Moonlight and Agria. The difference in WUE, between WUE in Moe Moe and modern potato under irrigation, is a result of late maturity in Moe Moe. Late maturity increased potential evapotranspiration, thus resulting in lower WUE in Moe Moe than modern potato. However, the WUE for Taewa under irrigation were still above the WUE of major world crops, such as rice, wheat and maize presented in literature review (Chapter 2).

This observation suggests that Taewa is more efficient under water stress compared to modern cultivars, which become more efficient when adequate water is available. Notably, low HI, an increased number of tubers per plant and a major disparity in appropriate agricultural husbandry practices, contribute to low yields and WUE in Taewa, in New Zealand. Apparently, appropriate water management will improve the total production of Moe Moe, unlike the case of Tutaekuri.

4.3.1.4.6 Specific gravity and tuber dry matter content

Taewa had the highest SG and DM compared to modern cultivars, thus indicating great genotypic differences in tuber quality. Such DM and SG differences have been reported in several studies (Werner *et al.,* 1998; Bélanger *et al.,* 2002; Singh *et al.,* 2008). However, the SG range in Taewa (especially Tutaekuri) is above the normal SG range of 1.055 to 1.0950 (Kellock *et al.,* 2004). Similar results (SG as high as 1.12 in potato) were reported by Verma *et al.,* (1971). Taewa results on SG and DM substantiate Singh’s (2008) findings that also reported a high SG and DM in Moe Moe and Tutaekuri, compared to the modern cultivar, Nadine, apart from confirming the glasshouse results presented in Chapter 3. It is probably that heredity and the long growing cycle for Taewa enhances the accumulation of DM, which results in high SG. Werner *et al.* (1998) reported that SG increases with a long growing season.

However, the study did not affirm reports on the effect of environmental manipulation on SG and DM (Killick *et al.,* 1974; Kellock *et al.,* 2004). Soil moisture hardly affected SG, as also reported in Russet Burbank and Shepody’s potato cultivars (Bélanger *et al.,* 2002). It is likely that the soil moisture modification was within the crop water requirement range for potato and hence, it could not influence SG and DM.

4.3.1.4.7 Total sugars

Moonlight had the highest total sugars followed by Agria, compared to Taewa. The concentration of sugars and DM in potato are usual benchmarks for processing potato quality assessment (Marquez *et al.,* 1986). High sugars badly affect colouring in potato fries (Marquez *et al.,* 1986; Kumar *et al.,* 2004), whereas high DM increases productivity of the processed product and the amount of oil used in chips (Kellock *et al.,* 2004). This finding suggests that Taewa can produce more processed products with less oil, compared to modern potato cultivars. Maori people might have wanted to grow Taewa because of its high solid and mealiness texture that easily meets their food and cooking satisfaction (Singh *et al.,* 2008). In addition, Maori people believe that Taewa has nutritional attributes which can control particular health problems (McFarlane, 2007).

4.3.1.5 Conclusion

The results of this research indicates that irrigation and cultivars influence potato tuber yield and yield components. Modern cultivars had the least number of tubers per plant and the highest mean tuber weight, whilst the Taewa variety, Tutaekuri had the highest number of tubers per plant and the least mean tuber weight. Moe Moe was intermediate in both traits. The total and marketable tuber yields of Agria, Moonlight and Moe Moe increased with irrigation under both environments. Moe Moe's yield was similar to modern cultivars but Tutaekuri was different. It can be concluded that some Taewa cultivars have comparable tuber yield and WUE to modern cultivars. Nevertheless, their increased vegetative growth**,** the higher number of tubers and inappropriate agricultural husbandry practices, contribute to low yields. Irrigation is recommended for Taewa and the best cultivars need to be used, due to genotypic influences (e.g. subspecies): Moe Moe can be irrigated in the expectation of high tuber yields.

SECTION 4.3.2

OCA CULTIVARS' RESPONSE TO IRRIGATION AND RAIN-FED CONDITIONS

4.3.2.1 Introduction

Oca (*Oxalis tuberosa* Mol.) is one of the important Andean tuber crops grown in New Zealand and it is commonly known as New Zealand yam (Sangketkit *et al.*, 2000). Oca has been commercialised in New Zealand, Mexico, Australia, France, Great Britain and Peru (Bormejo *et al.*, 1994; Collins, 1993 and Flores *et al.*, 2002, 2003). Its use is generally restricted by its low yields, both in New Zealand (Ross, 1999) and in the Andean region (Bormejo *et al.*, 1994; Sperling *et al.*, 1990). The low attainable yield in oca is a consequence of insufficient research and published agronomic work, despite its economic potential. The information available in New Zealand is related to its genetic characterisation (Martin *et al.*, 1999; 2005); storage and processing (Flores *et al.*, 2002); and utilisation and biochemistry (Dubios, 2007). Farmers tend to manage water and other resources in oca crops by trial and error (Pers. Comm. Osborne, 2009; Martin *et al.*, 1999).

The literature shows that other root and tuber crops yields (such as potato) are strongly influenced by water availability and genotypes (Belanger *et al.*, 2002; Walworth *et al.*, 2002). Oca farmers in New Zealand require scientific information on how to optimise their profits through cultivar selection and management of inputs, such as irrigation. Nevertheless, there have been very few studies of oca and in particular their response to irrigation. This study investigated the effects of irrigation on tuber yield, tuber development and WUE of two oca cultivars.

4.3.2.2 Materials and Methods

All details of the oca experiment materials and methods are presented in the general methodology section 4.2 above. This chapter section presents the results on plant physiological and morphological characteristics, yield and WUE for oca.

4.3.2.3 Results

4.3.2.3.1 Crop water use and soil moisture content

The growing season for oca was 224 days with a seasonal potential crop water requirement of 678 mm. Precipitation supplied 77% of the potential water requirement (Fig. 4.2.1). Irrigation added 200 mm, to meet at least 100% of the crop's water requirement in the irrigated treatment (Fig. 4.2.2). The crop water use for rain-fed was 75% of the irrigated crop (Table 4.2.2). Irrigation reduced the soil moisture deficit experienced between February and April, when precipitation was small (Fig. 4.2.1b, Appendix 4.4.2). This was evidenced by significant volumetric soil moisture content (%) variations between water regimes and measured dates (P<0.0001). Soil moisture in the rain-fed treatment was lower and it ranged between 15-20%, whilst irrigated treatments ranged between 20-35% (Fig. 4.2.1).

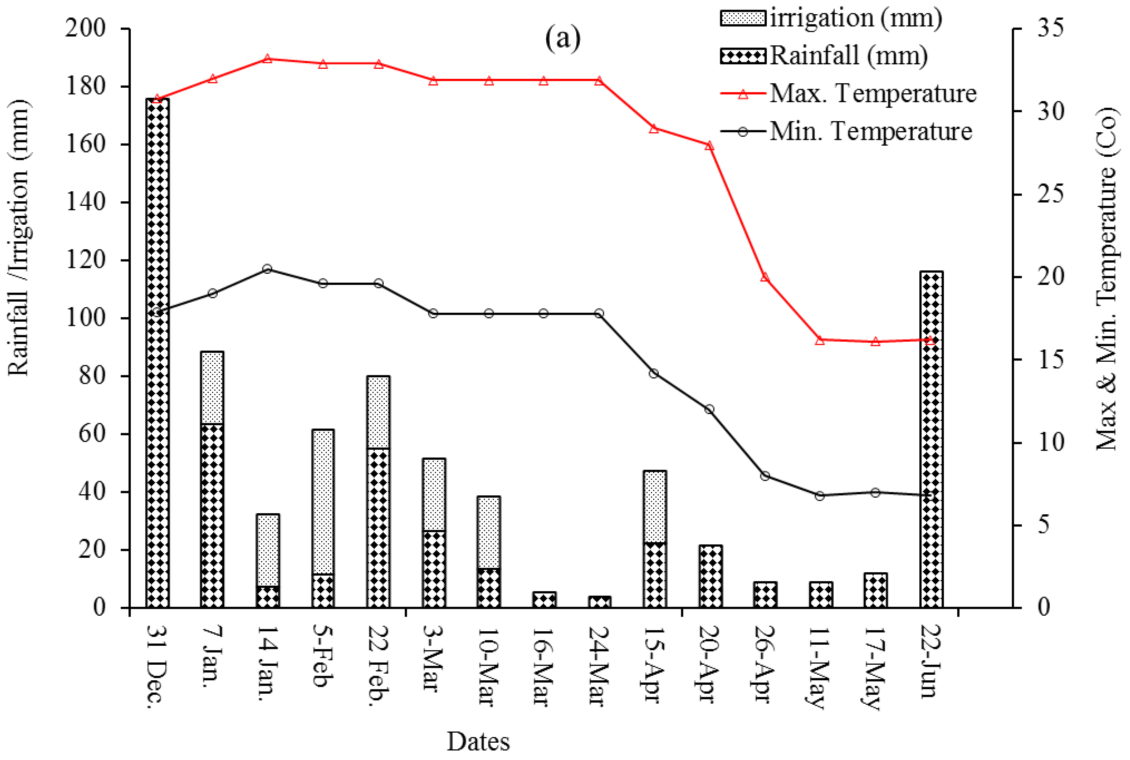


Figure 4.2.1 (a) Rainfall distribution, irrigation, maximum and minimum temperature during the growing season, 2009/2010

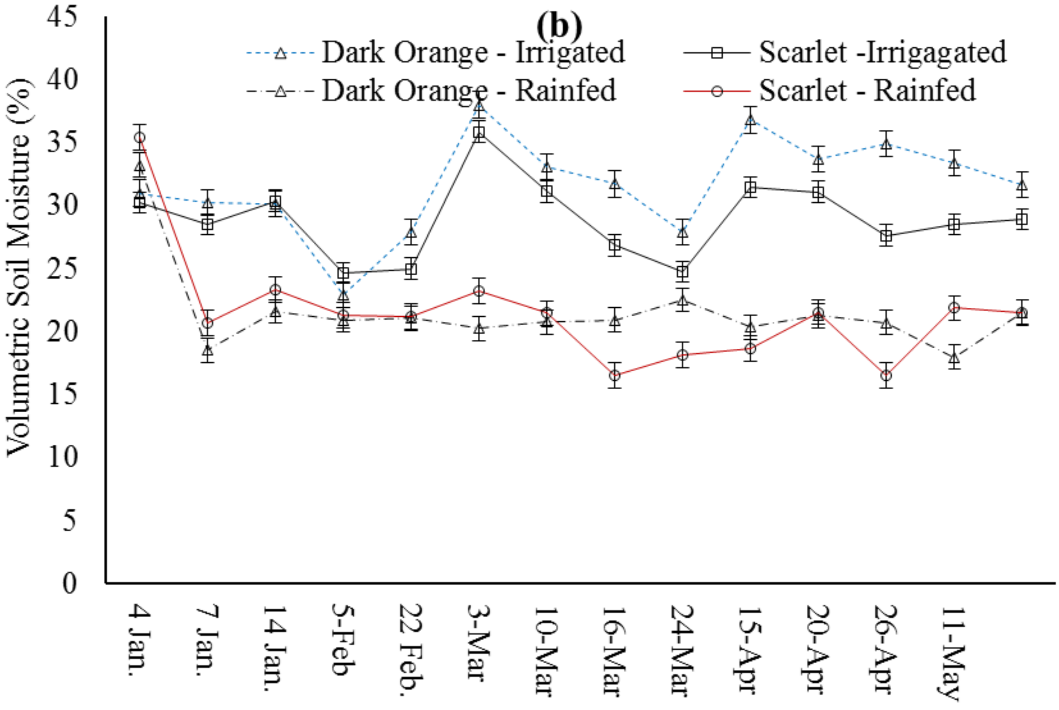


Figure 4.2.1 (b) Soil moisture content change during the growing season. Error bars represents ±SEM.

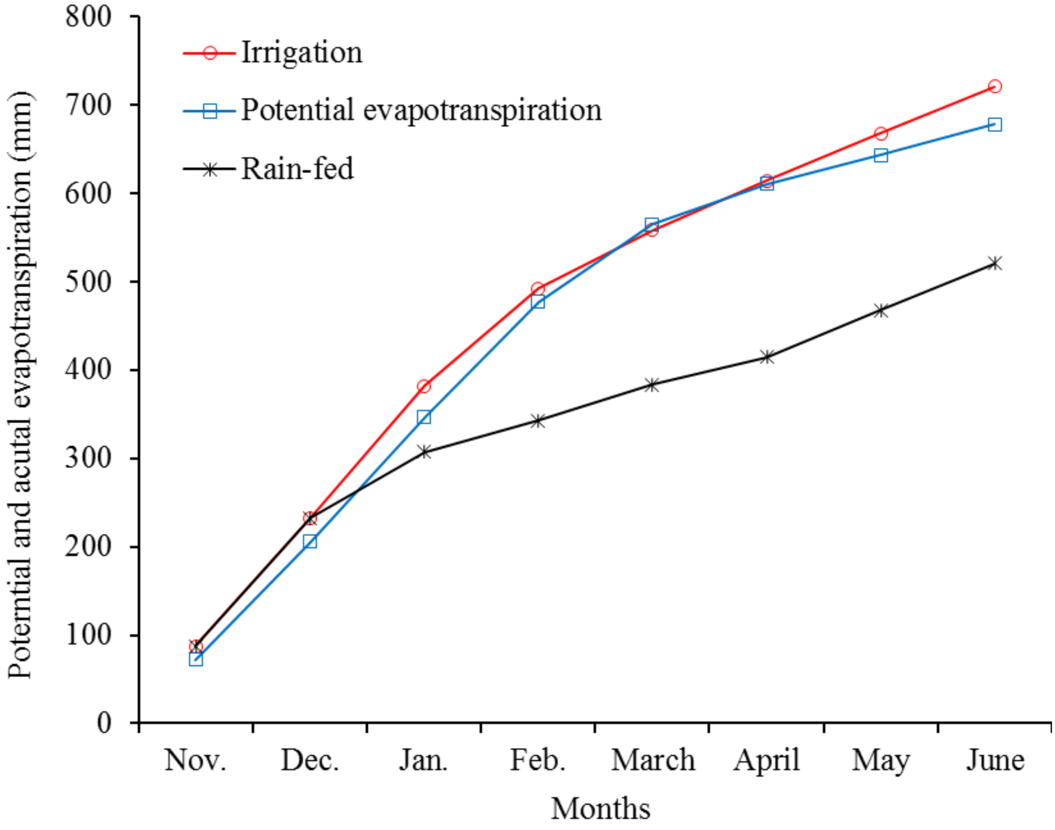


Figure 4.2.2 Potential and Actual crop water use (mm) under rain-fed and full irrigation for oca, 2009/2010

4.3.2.3.2. Photosynthetic water use efficiency and gaseous exchange

Net photosynthesis ($A_{n,}$ µmolCO_2 m^2 s^{-1}); photosynthetic WUE (µmolCO_2/m molH_2O); and VPD (mb) were significantly influenced by the water regime ($P<0.05$, $P<0.05$, $P<0.01$) (Table 4.2.1). Oca cultivars had no significant effect on gaseous exchange ($P>0.05$). Net photosynthesis, T, g_s, photosynthetic WUE, Ci and VPD significantly differed between DAE ($P<0.001$, $P<0.01$, $P<01$, $P<0.0001$, $P<0.01$, $P<0.0001$) (Table 4.2.1). The irrigation treatment had the highest A_n and photosynthetic WUE and lowest VPD, whilst the rain-fed regime had low A_n and photosynthetic WUE and highest VPD and Ci. Net photosynthesis and photosynthetic WUE increased from Day 21 to Day 48, before it decreased at Day 64 and increased again on Day 90, before decreasing again on Day 157.

The trend for gaseous exchange in oca shows net photosynthesis and photosynthetic WUE decrease on Day 64 and 157 following high VPD and low leaf stomata conductance (g_s), under rain-fed conditions. The relationship between photosynthetic WUE and gaseous exchange variables was explored with all data combined and using simple correlation. It was found that photosynthetic WUE negatively correlated with T ($r = -0.58$, $P<0.0001$); Ci ($r = -0.40$, $P<0.01$); VPD ($r = -0.59$, $P<0.0001$); and positively correlated with A_n ($r = 0.73$, $P<0.0001$) and g_s ($r = 0.34$, $P<0.01$).

Table 4.2.1 Photosynthetic water use efficiency and gaseous exchange in two oca cultivars under irrigation and rain-fed conditions

Water regime/ Cultivar/DAE	Net Photosynthesis A_n ($\mu molCO_2\ m^2\ s^{-1}$)	Transpiration (T) ($m\ molH_2O\ m^2\ s^{-1}$)	Stomata Conductance g_s ($m\ mol\ CO_2\ m^2\ s^{-1}$)	Photosynthetic WUE ($\mu molCO_2/m\ molH_2O$)	Internal Carbon concentration (Ci) (ppm)	Vapour Pressure Deficit (VPD) (mb)
Water regime						
Irrigation	21.9^{a}	3.1	613.6	7.4^{a}	293.6	6.6^{b}
Rain-fed	19.2^{b}	3.2	566.9	6.2^{b}	301.8	7.9^{a}
Significance	$P<0.05$	Ns	Ns	$P<0.05$	Ns	$P<0.01$
Cultivars						
Dark Orange	20.7	3.2	623.7	6.7	298.3	7.1
Scarlet	20.5	3.1	556.8	6.9	297.1	7.4
Significance	Ns	Ns	Ns	Ns	Ns	Ns
Days after emergence (DAE)						
21	20.2^{c}	3.3^{c}	536.5^{b}	6.5^{bc}	294.1^{bc}	7.7^{bc}
48	23.0^{b}	2.6^{e}	725.7^{a}	9.2^{a}	303.6^{b}	4.4^{d}
64	15.8^{d}	3.4^{b}	539.6^{b}	4.9^{e}	319.3^{a}	8.8^{a}
90	24.1^{a}	3.5^{a}	675.8^{a}	7.1^{b}	282.4^{c}	7.0^{c}
157	19.4^{c}	3.2^{d}	445.8^{c}	6.2^{c}	289.9^{c}	8.3^{ab}
Significance	$P<0.001$	$P<0.01$	$P<0.01$	$P<0.0001$	$P<0.01$	$P<0.0001$

Note : The columns with similar letters within column rows are significantly different at the probability level of 5%

4.3.2.3.3 Tuber growth and development

Tuber fresh biomass of oca varied between the sampling dates ($P<0.0001$, Fig. 4.2.3). There was no tuber formation prior to 100 days from planting. Tubers were initially observed as developing in the irrigated dark orange oca (4.8 g plant^{-1}) and scarlet oca (13.8 g plant^{-1}), 132 days after planting (DAP) (22nd March) (Fig.4.2.3b). The tuber biomass slightly increased in the irrigated dark orange and scarlet oca to 68.6 g and 65.4 g per plant, compared to the rain-fed dark orange and scarlet oca, which had only developed up to 26.6 g and 52.7 g per plant, after 154 DAP (13th April), respectively. The tuber biomass for rain-fed (on this date) was 38.8% and 80.6% of irrigated dark orange and scarlet oca, respectively.

By 3rd May, the tuber biomass had increased in the irrigated dark orange and scarlet oca to 502 g and 521 g per plant, whilst the rain-fed dark orange and scarlet oca had increased to 355.5 g and 470.4 g per plant. The rain-fed dark orange and scarlet oca tubers were still at a lower level (compared to the irrigated plants) at 70.8% and 90.3%, respectively.

Final tuber fresh biomass for irrigated dark orange and scarlet oca was 608.1 g and 669.4 g per plant, whilst rain-fed dark orange and scarlet oca was 439.1 g and 556.1 g per plant, at harvest (Fig. 4.2.3). The total tuber biomass per plant, for rain-fed, was between 72% and 83% of the irrigated tubers at harvesting. The tuber growth rate increased as the days' length shortened up to May and then it declined in June (Fig.4.2.3a). The highest tuber growth rate, which ranged from 14.45-15.2 g per day and 10.96-13.92 g per day in irrigated and rain-fed dark orange and scarlet, respectively, was observed in May (Fig.4.2.3a).

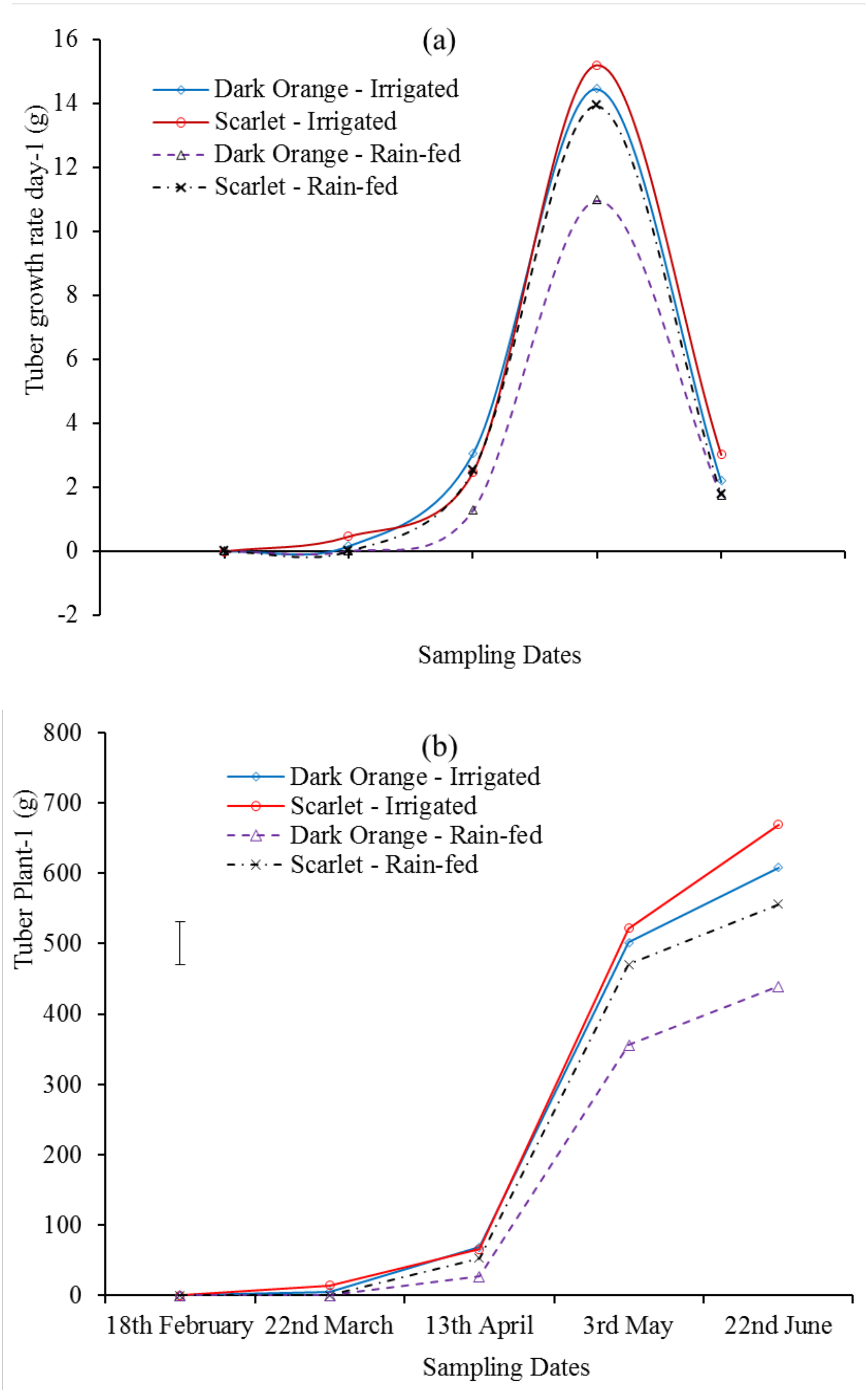


Figure 4.2.3 (a) Oca tuber growth rate (g/day) and (b) tuber biomass (g/plant) at different sampling dates on fresh weight basis. Error Bar is ±SEM

4.3.2.3.4 Total and marketable tuber yield, yield components and WUE

Irrigation had a significant effect on total tuber yield and the number of tubers per plant ($P<0.05$), but it had no effect on average tuber weight ($P>0.05$). Cultivar influenced the number of tubers per plant ($P<0.05$) (Table 4.2.2). The total tuber yield was strongly influenced by the number of tubers per plant, rather than the average tuber weight.

Marketable tuber yield and marketable tuber yield components were not different between oca cultivars, but they were different between water regimes. Table 4.2.2 shows that the number of L-grade marketable tubers, L-grade marketable tuber yield and total marketable tuber yield were influenced by irrigation ($P<0.01$, $P<0.01$, $P<0.05$), whereas medium grades (M-grades) were not influenced by irrigation ($P>0.05$) (Table 4.2.2). The WUE evaluated, based on total tuber yield at harvest per volume of water used was not significantly influenced by irrigation or cultivar ($P>0.05$; Table 4.2.2). The WUE ranged between 3.3-3.7 (kg ha^{-1} m^{-3}) (Table 4.2.2).

4.3.2.4 Discussion

4.3.2.4.1 Crop water use and soil moisture content

The oca growing season in the Andean region is between 6 - 8 months with a water requirement of 400 - 700 mm (Arbizu *et al.*, 1997; King, 1987). The study found 678 mm as being the potential water requirement within 7.5 months. The result also indicates that oca water requirement is within the range of potato (500 - 700 mm) (Allen *et al.*, 1998; Shock *et al.*, 2007). However, oca water use might be more variable, due to weather variability within its extended crop life-cycle, in contrast to potato. This proposition is not in agreement with what Flores *et al.* (2003) once speculated that oca may require up to 2500 mm of water for production. Irrigation was important for this crop in order to maintain optimal soil moisture during growth and tuber development stages (Fig.4.2.1a-b and Fig. 4.2.3).

Table 4.2.2 Total yield, yield components and WUE for oca under irrigation and rain-fed conditions, 2009/2010

Water regime/ Cultivars	Tubers Per plant	Av. Tuber Weight (g)	Total Tuber Yield ($t\ ha^{-1}$)	WUE ($kg\ m^{-3}$)	Number of marketable tubers $plant^{-1}$		Marketable Tuber mean weight (g)		Marketable Tuber Yield ($t\ ha^{-1}$)		
					M-Grade	L-Grade	M-Grade	L-Grade	M-Grade	L-Grade	Totals
Irrigation											
Dark Orange	60.4	9.9	23.2	3.4	8.5	5.3	15.6	27.6	5.1	5.2	10.2
Scarlet	74.1	9.1	25.5	3.7	8.8	4.6	17.1	28.7	5.4	4.9	10.2
Mean	67.3	9.5	24.3	3.6	8.7	5.0	16.4	31.4	5.2	5.0	10.2
Rain-fed											
Dark Orange	53.2	8.2	16.7	3.3	6.4	1.3	15.3	28.7	3.7	1.4	5.1
Scarlet	62.3	9.0	21.2	4.2	7.7	2.7	15.7	34.1	4.3	3.3	7.6
Mean	57.7	8.6	19.0	3.7	7.1	2.0	15.5	28.1	4.0	2.4	6.4
Cv. (%)	13.8	10.6	18.7	18.9	20.6	39.9	33.7	17.7	29.0	31.0	24.5
Significance											
Cultivars	$P<0.05$	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
Regime	$P<0.05$	Ns	$P<0.05$	Ns	Ns	$P<0.01$	Ns	Ns	Ns	$P<0.01$	$P<0.05$
$LSD_{0.05}$	9.73	1.08	4.57	-	1.83	1.56	6.07	5.94	1.51	1.30	2.30

4.3.2.4.2 Photosynthetic water use efficiency and gaseous exchange

Water stress increases the leaf VPD resulting in limited photosynthesis in plants (Bunce, 2003, 2009). The results confirmed that water stress (under rain-fed) increased leaf VPD in oca, whilst irrigation reduced it. Consequently, photosynthetic WUE and A_n were reduced under rain-fed with high VPD [A_n= - 0.64 (VPD) + 25.2, r = 12.4, P<0.01], compared to irrigated plots. This observation suggests that the high leaf VPD in the rain-fed treatment was caused by leaf water deficit and a reduced water supply to the roots of the oca (Monteith *et al.,* 1986). Irrigation closed the gap of moisture deficit between the leaf and the surrounding air, by supplying more water to the roots, regardless of cultivar. Judging from the leaf vapour pressure deficit and photosynthetic results, water deficit is one of the major limiting factors for high photosynthetic WUE in oca.

4.3.2.4.3 Tuber formation and growth

Oca tuber biomass and growth rate increased, as day length shortened, confirming that it is day-length reliant and that tubers develop as day length become shorter after the autumnal equinox (Arbizu *et al.,* 1997; Martin *et al.*, 2005). In this case (22nd March), the autumnal equinox day for the southern hemisphere is the time that the oca tuber starts forming in New Zealand. However, the effect of temperature on tuber formation needs to be thoroughly investigated, since short days are always accompanied by lower temperatures. This study also suggests that photo-period sensitivity restricts oca from being adapted in other parts of the world (Sperling *et al.*, 1990; Martin *et al.*, 2005).

Apart from the day-length effect, tuber set and growth was delayed in rain-fed, indicating the adverse effects of water stress on tuber setting and development, as also observed in photosynthesis above. A similar response to water stress has also been reported in potato (Shock *et al.*, 2007). This leads to the conclusion that optimal water is essential for oca tuber formation and development during the autumn period.

4.3.2.4.4 Total tuber yield, marketable tuber yield and tuber yield components

Irrigation enhances total and marketable tuber yield in oca, similarly to potato (Erdem *et al.*, 2006; Ferreira *et al.*, 2007). Oca responded to irrigation primarily through an increase in tuber numbers per plant, thus resulting in increased total tuber yield (Table 4.2.3). The genotypic variation in tuber numbers has also been reported in potato. However, most potato cultivars are accompanied by average tuber weight variation under irrigation (Bélanger *et al.*, 2002). In this study, irrigation enhanced total tubers per plant (depending on the cultivar) and it enhanced the number of premium marketable tubers, regardless of cultivar. The study shows that development of premium marketable tubers in oca production is more governed by adequate water than cultivar.

The premium marketable tubers of oca were a result of the enhanced allocation of assimilates to tubers with adequate moisture. Irrigation almost doubled the marketable tuber yield through tuber enlargement. There is substantial evidence that irrigation modified the number of premium marketable tubers, as in potato (*Solanum tuberosum*) (Ferreira *et al.*, 2007; Shock *et al.*, 2007). Furthermore, irrigation enhanced photosynthetic WUE and A_n. This substantiated the adverse response of oca to water stress and it verifies that oca total and marketable yields are well enhanced with optimal soil moisture.

On the other hand, the tuber yields obtained under rain-fed, in this study, were higher than those reported in the Andean region (3-12 t ha^{-1}) (Bormejo *et al.*, 1994): but they were within those levels reported in New Zealand (12-16 t ha^{-1}) (Martin *et al.*, 1999). Total tuber yields under irrigation demonstrate the possibility of doubling the present oca yields in New Zealand and the Andean region if optimal water management is used (King, 1987). The tuber yield increase with optimal water and nutrients, which have been thoroughly documented in relation to modern potatoes (Ferreira *et al.*, 2007; Shock *et al.*, 2007), can be readily achieved in oca. However, oca is not efficient in its water use and its crop water productivity is strongly affected by its long life of 224 days. This confirmed by its equal WUE between irrigation and non-irrigated treatments. The usual trend in potato and other crops is that highest WUE is in non-irrigated (Battilani *et al.*, 2004; Zoebl, 2006). The implication of this result is that water management in oca should be of great concern, because water can only be optimised through correct phenology manipulation, or by using agronomic practices which will improve WUE but not selection of cultivars (Boutraa, 2010).

4.3.2.5 Conclusion

The results of the study indicated an adverse reduction in photosynthetic water use efficiency; increased leaf vapour pressure deficit; and reduced tuber growth and development in rain-fed oca, compared to irrigated oca. Oca total yield and marketable yield improved under irrigation, regardless of crop cultivar. WUE was found to be strongly affected by the oca long lifecycle. It can be concluded that oca is short-day dependent and that tuber set, total yield and marketable yield, are highly enhanced with irrigation, which is similar to potato. However, WUE in oca is not efficient, as seen in potato. Its crop water productivity is strongly influenced by its high potential evapotranspitation, which is sustained from its long lifecycle.

SECTION 4.3.3

MODERN AND HERITAGE PUMPKIN SQUASH CULTIVARS' RESPONSE TO IRRIGATION AND RAIN-FED CONDITIONS.[3]

4.3.3.1 Introduction

Kamokamo (*Cucurbita pepo* Linn*)* is a heritage pumpkin cultivar originally grown by the Maori people of New Zealand (McFarlane, 2007). Generally, it sells in a niche market, in contrast to Buttercup squash *(Cucurbita maxima* Duchesne), which is an important commodity crop exported to Japan and Korea (Hume, 1982; Perry *et al.*, 1997). However, there has been a resurgence of interest in Kamokamo, due to its cultural value and delicious flavor. Market demand has also facilitated an increase in Buttercup squash production in New Zealand (Grant *et al.,* 1989), Tasmania and Korea, whilst Japan recorded a yield decrease (Morgan *et al.*, 2003). On the other hand, the Buttercup squash industry experiences fruit yield and fruit size fluctuations between seasons due to the pumpkin squash's sensitivity to seasonal climate variability (Perry *et al.,* 1997).

Pumpkin squash yield and standard fruit size are strongly influenced by water availability and also by genotypic variability (Al-Omran *et al.,* 2005; Ertek *et al.,* 2004). New Zealand farmers need to be able to manage pumpkin squash fruit quality and water conservation due to a projected water scarcity (IWMI, 2000). Prudent use of water resources (Hoekstra *et al.,* 2007) and the correct pumpkin cultivars will help growers to meet yield and quality demands, which will maximize financial returns (Searle *et al.*, 2003) within adverse climate variability (Perry *et al.,* 1997). However, there is scarce scientific information on the agronomic performance of pumpkin squash under different water environments in New Zealand. This field experiment was conducted, in order to measure fruit yield, WUE and fruit size distribution in Buttercup squash, compared to the heritage cultivar, Kamokamo, under irrigation and rain-fed conditions.

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[3] **Section 4.3.3 is published as:** Fandika, I.R Kemp, P.D., Millner, J.P and D. Horne (2011). Yield and water use efficiency in (*Cucurbita maxima* Duchesne) Buttercup squash and (*Cucurbita pepo* Linn) heritage pumpkin cultivar. *Australian Journal of Crop Sciences,* 5(6):742-747

4.3.3.2 Materials and Methods

All the details of the pumpkin squash experiment materials and methods are presented in the general methodology section (4.2) above. The following section presents the results on plant physiological and morphological characteristics, fruit yield and WUE for pumpkin squash.

4.3.3.3 Results

4.3.3.3.1 Crop water use and soil moisture content

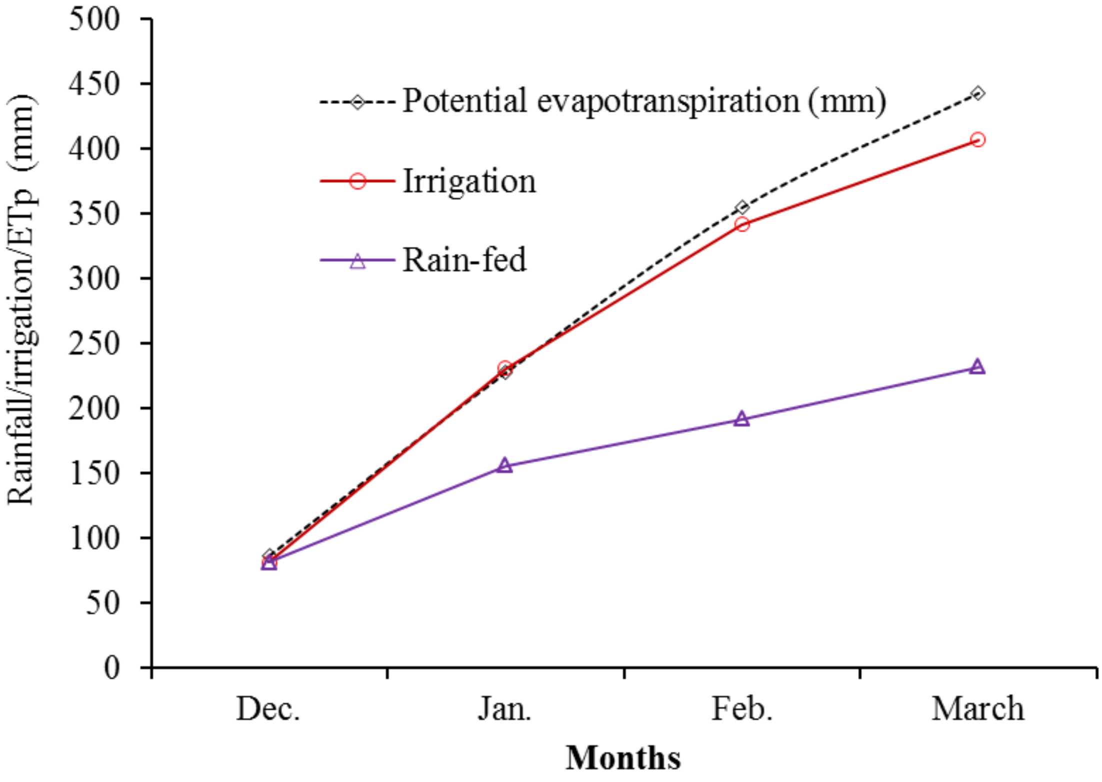


Figure 4.3.1 Potential and actural crop water use (ET_c) (mm) under rain-fed and full irrigation for pumpkin squash, 2009/2010.

The growing season for the pumpkin squash was from 9th December, 2009 to 30th March, 2010 (110 days), which is equivalent to 3.7 months. The seasonal crop water requirement for the pumpkin squash was estimated at 442.1 mm (Fig. 4.3.1). Precipitation supplied 232.8 mm, which was 53% of the estimated total water requirement. Irrigation added 175 mm, which met at least over 90% of the crop water requirement within the irrigated treatment. The rain-fed Buttercup and Kamokamo used 258.7 mm and 264 mm, whilst the supplementary irrigated crops used 407.6 mm and

413.2 mm, respectively. Irrigation was a requirement in January, February and March when precipitation was poorly distributed (Fig.4.3.1, Fig.4.3.2 and Appendix 4.4.2).

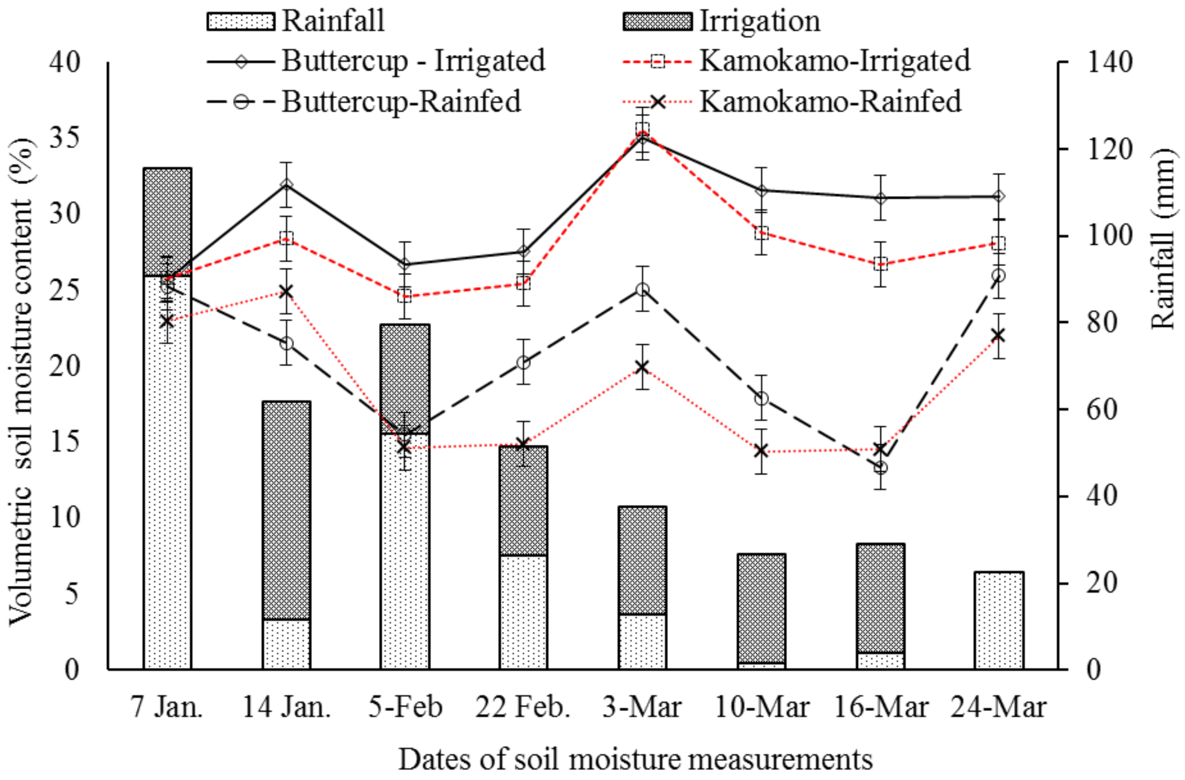


Figure 4.3.2 Volumetric soil Soil moisture measurements corresponding to periodical precipitation (mm) and irrigation (mm), 2009/2010. Error bar represents ±SEM.

Volumetric soil moisture content (%) differed with water regimes and crop cultivars and between measurement dates ($P<0.0001$, $P<0.05$, $P<0.0001$), respectively (Fig. 4.3.2). Soil moisture in rain-fed treatments ranged between 15 - 25%, whilst irrigated treatments ranged between 20 - 35%, except in February when soil moisture was depleted to less than 20%. Kamokamo extracted more water than Buttercup squash in both water regimes.

4.3.3.3.2 Pumpkin squash growth and yield components characteristics

With or without irrigation, pumpkin squash cultivars differed in LAI at all four different sampling stages ($P<0.0001$; Table 4.3.1; Fig. 4.3.3). Kamokamo had a higher LAI and SLA, compared to Buttercup squash. The LAI increased from Day 21 to Day 80 (from emergence). Leaf area index was sporadically reduced by frost in the month of March, 2010. Buttercup flowered earlier than Kamokamo ($P<0.0001$), regardless of the water regime ($P>0.05$).

The number of fruit per plant was unaffected by irrigation (P>0.05). The mean fruit weights were significantly higher in Kamokamo under a rain-fed regime (P<0.05), but there was no difference within the irrigated treatments. The mean fruit size had more influence on fruit yield, compared to the number of fruit (Table 4.3.1; Plate 4.3.1).

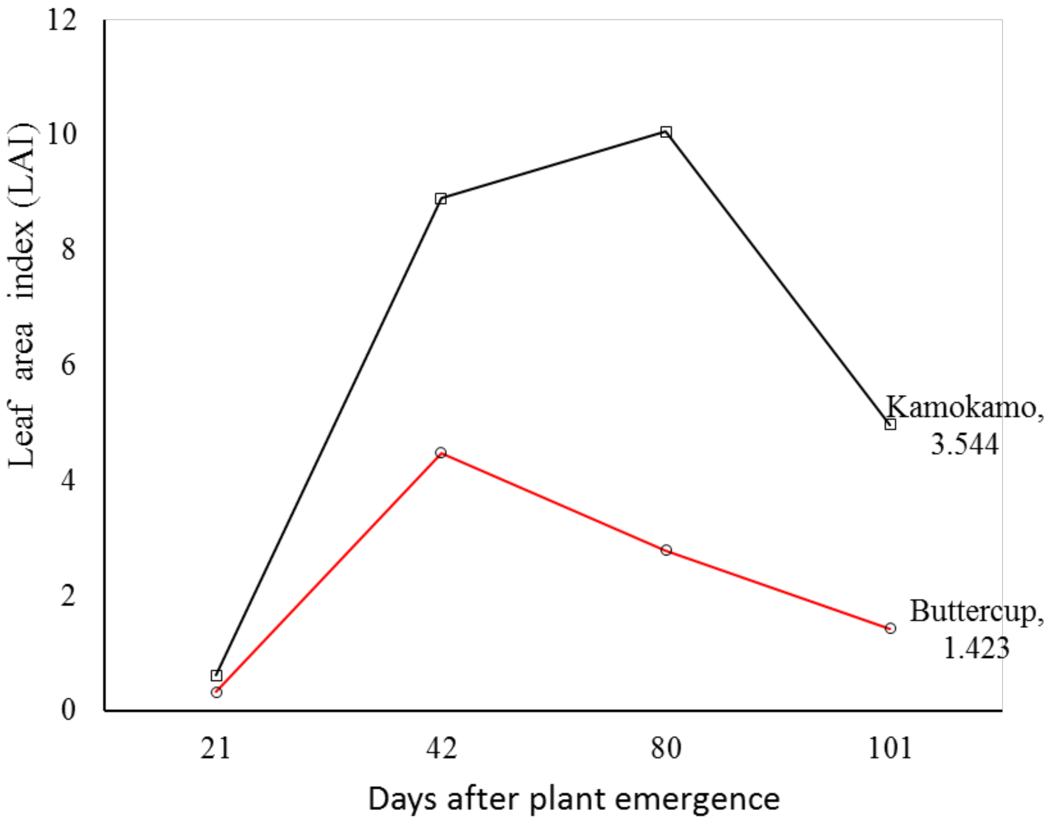


Figure 4.3.3 Change of LAI in Buttercup squash and Kamokamo during the growing season

4.3.3.3.3 Pumpkin squash fruit size distribution

The fruit size distribution for large marketable fruits (L=1.4–2.5 kg) was significantly higher than other fruit size ranges (P<0.05; Fig. 4.3.4; Plate 4.3). The irrigated treatments had a higher percentage of fruit within this fruit size range (L=1.4 – 2.5 kg): the highest was seen in the irrigated Buttercup squash (82.9%). Kamokamo had more extra-large fruit and small non-marketable fruits than Buttercup squash, especially under rain-fed conditions (Plate 4.3).

(a) Irrigated Kamokamo (b) Rainfed Kamokamo

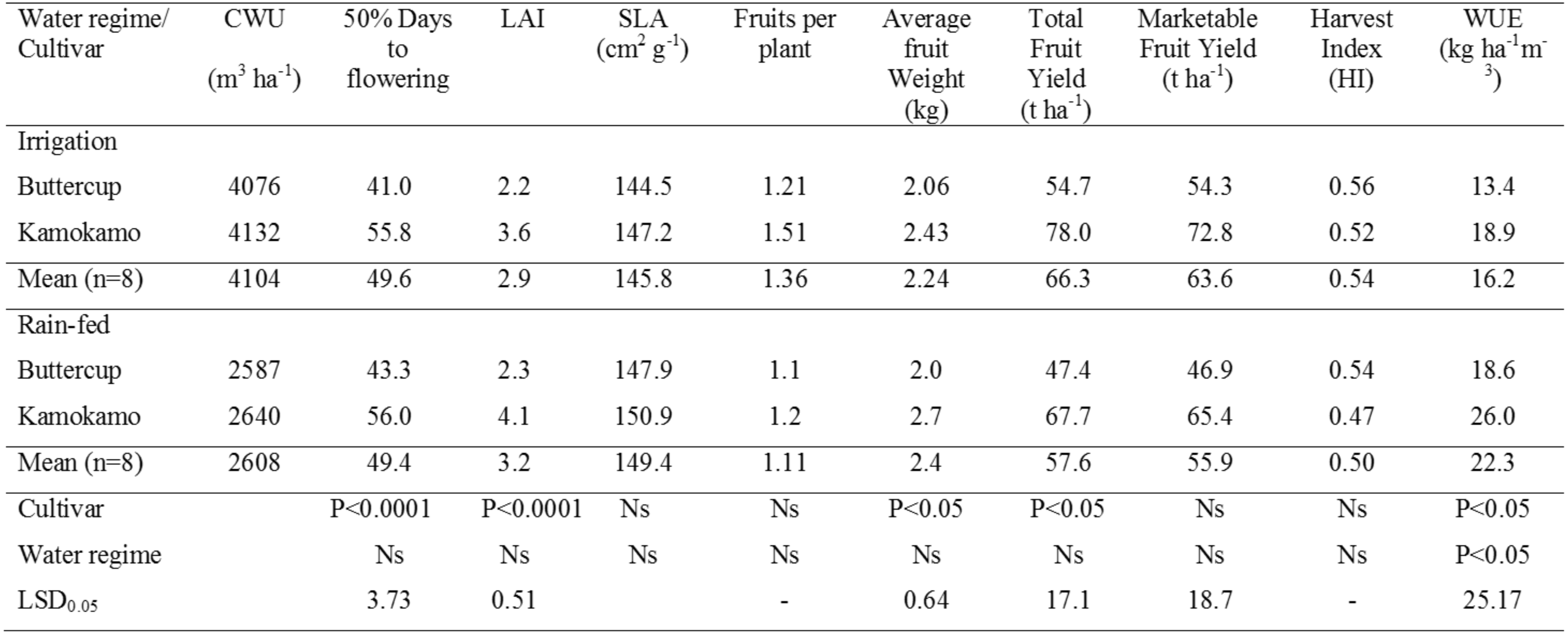
(c) Irrigated Buttercup (d) Rainfed Buttercup

Plate 4 3 : A sample of pumpkin squash fruit size distribution under different water regimes per plot.

4.3.3.3.4 Pumpkin squash fruit yield and water use efficiency (kg $ha^{-1}m^{-3}$)

With or without irrigation, the amount of dry vines plus leaves per hectare and total fruit yield varied in Buttercup squash and Kamokamo, respectively ($P<0.0001$, $P<0.05$;Table 4.3.1). Marketable fruit yield and HI did not differ between the two cultivars and their water regimes ($P>0.05$). Kamokamo prevailed over Buttercup squash in all the above traits, except in HI. The high LAI did affect HI in Kamokamo. Although the water regimes did not affect the fruit yield, there were minor levels of water stress effects seen in the reduction of HI and fruit yield under the rain-fed conditions (Table 4.3.1). Most of the non-marketable fruit was based on immaturity and low fruit weight (<1 kg), rather than disease impairments. WUE, based on total fruit yield per total water used, was affected by both the water regime and the crop cultivars ($P<.05$, $P<0.01$; Table 4.3.1). Kamokamo had a higher WUE than Buttercup squash.

Table 4.3.1 Growth and fruit yield components characteristics, total and marketable fruit yield, HI and WUE for Buttercup squash and Kamokamo



Water regime/ Cultivar	CWU (m^3 ha^{-1})	50% Days to flowering	LAI	SLA (cm^2 g^{-1})	Fruits per plant	Average fruit Weight (kg)	Total Fruit Yield (t ha^{-1})	Marketable Fruit Yield (t ha^{-1})	Harvest Index (HI)	WUE (kg $ha^{-1}m^{-3}$)
Irrigation										
Buttercup	4076	41.0	2.2	144.5	1.21	2.06	54.7	54.3	0.56	13.4
Kamokamo	4132	55.8	3.6	147.2	1.51	2.43	78.0	72.8	0.52	18.9
Mean (n=8)	4104	49.6	2.9	145.8	1.36	2.24	66.3	63.6	0.54	16.2
Rain-fed										
Buttercup	2587	43.3	2.3	147.9	1.1	2.0	47.4	46.9	0.54	18.6
Kamokamo	2640	56.0	4.1	150.9	1.2	2.7	67.7	65.4	0.47	26.0
Mean (n=8)	2608	49.4	3.2	149.4	1.11	2.4	57.6	55.9	0.50	22.3
Cultivar		$P<0.0001$	$P<0.0001$	Ns	Ns	$P<0.05$	$P<0.05$	Ns	Ns	$P<0.05$
Water regime		Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	$P<0.05$
$LSD_{0.05}$		3.73	0.51		-	0.64	17.1	18.7	-	25.17

4.3.3.4 Discussion

It is claimed that pumpkin squash fruit yield increases with increasing water application and declines when water is in excess or limited (Al-Omran *et al.,* 2005). In this study, fruit yield failed to respond to irrigation, possibly due to rainfall that made the soil wet soon after irrigation. Consequently, the after irrigation rainfall spatially reduced fruit yield response to irrigation. In spite of this, irrigation influenced the standard fruit size for the export market, both in Buttercup squash and Kamokamo (Fig. 4.3.4). The results on standard fruit size in Fig.4.3.4 indicate that, although irrigation may not be of significant importance for total fruit yield in a good year, it facilitates quality control for marketable fruit sizes, compared to rain-fed conditions (Fig.4.3.4 & Plate 4.3.1).

The results suggested that more flowers are sustained under irrigation than under rain-fed conditions. The fewer flowers maintained under rain-fed conditions translated into larger fruit than for irrigated conditions (Plate 4.3.1). There has not been a previous report on irrigation influence on pumpkin fruit size in New Zealand. However, lots have been reported by Fletcher *et al.* (2000) on how diseases reduce fruit number and size in Buttercup squash. In this study, irrigation played an important role in the reduction of pumpkin squash fruit variability. Perry *et al.,* (1997) reiterated that fruit size fluctuations are a great problem in pumpkin squash industry where specific fruit size is a requirement. Irrigation, in order to manipulate specific market fruit size, needs to be well modelled, as previously undertaken with plant density studies (Lima *et al.,* 2003).

Total yields and marketable yields were slightly greater than those obtained by the majority of growers in New Zealand (Buwalda *et al.,* 1987), Tasmania, Australia (Morgan *et al.,* 2003) and other parts of the world. The cultivar had more influence on the pumpkin squash yield, when the environment was not limiting, as also reported by Morgan *et al.* (2003). In this case, the results indicate that Kamokamo has a high fruit yield and WUE potential, compared to Buttercup squash. It was also observed that the high yield in Kamokamo was due to its ability to produce fruits of larger size than Buttercup squash. The high yield in Kamokamo, a *Cucurbita pepo* species contradicts St. Rolbiecki *et al.* (2000), who reported that *Cucurbita maxima* cultivars have high production efficiency, compared to the *Cucurbita pepo* species of pumpkin squash.

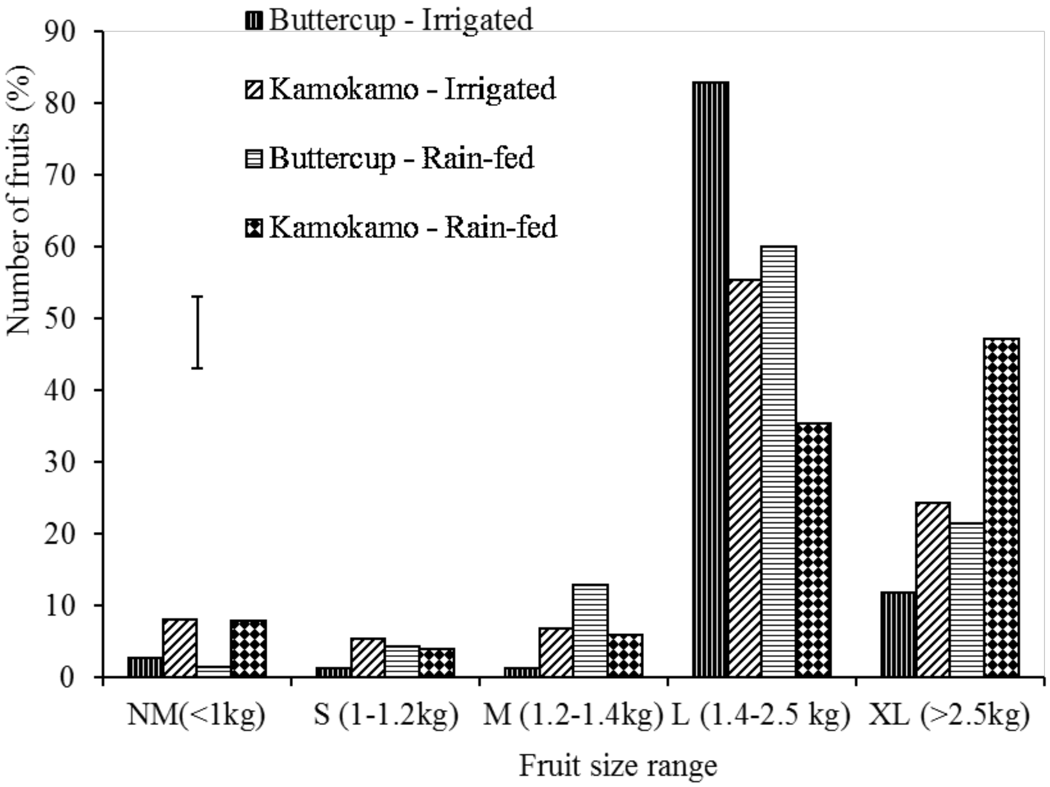


Figure 4.3.4 Number of size distribution (%) for irrigated and rain-fed Buttercup squash and Kamokamo: NM is non-marketable, S is small, M is medium, L is large and XL is extra large marketable fruit sizes. Error Bar represents $LSD_{0.05}$

Water use efficiency vary with crop types, management system, year or location (Nielsen *et al.*, 2006). In this study, Kamokamo (18.9 – 26 kg ha^{-1} m^{-3}) had a higher WUE than Buttercup (13.4 – 18.6 kg ha^{-1} m^{-3}). Irrigation decreased WUE, as also reported in potato (Battilani *et al.*, 2004) and other crops. Nevertheless, the value for WUE in Kamokamo and Buttercup were above those reported amongst the world's major crops (wheat, rice, maize, oat, potato, grain legume and forage grass) (FAO, 2009; Siddique, *et al.*, 2001). The WUE findings project that pumpkin squash has a high ability to transform water into more carbon than most of the world's major crops, including forage grass and potato. The possible reason for the high WUE in pumpkin squash is its high fruit yield within a low potential evapotranspiration, which is a result of a short growing season, compared to other major world crops and forage crops.

In this study, the old cultivar, Kamokamo, had more shoot biomass, fruit yield and WUE but it had low HI, compared to the modern cultivar, Buttercup squash. The high foliage and low HI supports Siddique *et al.* (1990a), who reported that modern crops have enhanced HI, whilst old cultivars have more foliage. The reason is that modern cultivars are bred for high HI. However, the improvement of HI in Buttercup squash did not increase fruit yield and WUE above Kamokamo, as reported in grain crops, where WUE was improved with the enhancement of HI in modern crops (Siddique *et al.*, 1990a). Primarily, fresh biomass is essential for determining production in cucurbit species, rather than HI (Loy, 2004). This indicates that Kamokamo, a heritage cultivar of New Zealand, has more potential for yield and WUE traits, than the modern Buttercup cultivar —and this potential needs to be fully exploited in the near future, within the pumpkin squash industry.

4.3.3.5 Conclusion

The results indicate that irrigation improves the development of standard marketable fruit sizes in pumpkin squash but not the total marketable fruit yield. The cultivars differed in total fruit yield and WUE. Increased water supply decreased WUE. The cultivar with the greatest WUE was that with greatest yield. Total fruit yields and WUE components, were highest in Kamokamo, which was a result of a high mean fruit weight, LAI and water extraction, respectively. On the other hand, both Kamokamo and Buttercup squash exceeded the WUE observed in major world crops. Pumpkin squash is a crop with high water productivity traits.

SECTION 4.3.4

COMPARISON OF KEY WATER USE EFFICIENCY INDICATORS FOR HERITAGE AND MODERN POTATO, PUMPKIN SQUASH AND OCA CULTIVARS

4.3.4.1 Introduction

Optimisation of yield and water use is of great concern in both modern and heritage crop production systems. Sections 4.3.1 – 4.3.3 confirm the importance of irrigation to yield improvements in some heritage and modern crop cultivars. Growers of these crops need knowledge of irrigation water use efficiency, economic water productivity and water footprints, in order to successfully grow these crops and to help them optimise resource use and maximise profitability (Barker *et al*., 2003; Hoekstra *et al.,* 2007). These concepts are becoming more important and they may influence future market access and water conservation targets in heritage and modern crop cultivars (MAF, 2004a).

Irrigation water use efficiency, economic water productivity and water footprints associated with the growing of arable crops have not been examined amongst modern and heritage crop cultivars in New Zealand. The following hypothetical questions were asked: *What is the impact of additional water input on the studied heritage crop cultivars compared to modern crop cultivars, in relation to yield or cash per water used? How much water is required to produce a tonne of specific heritage crop cultivars, compared to modern crop cultivars?* In order to answer these questions, this section analyses irrigation water use efficiency (IWUE); water stress index; economic water productivity (EWP); and water footprints (WF), when growing heritage and modern potato, pumpkin squash and oca cultivars under rain-fed or irrigation in New Zealand.

The section initially presents a summary of the crop water use and yield results from preceding sections, followed by water productivity results. The summary integrates all the studied crops to easily assess how the water productivity indicators (IWUE, EWP and WF), when growing heritage and modern potato, oca and pumpkin squash, can vary with crop management and cultivars.

4.3.4.2 Materials and Methods

The details of the field experimental design, crop and irrigation management are presented in Section 4.2. This section will only present the results on key water use efficiency indicators.

4.3.4.3 Results

4.3.4.3.1 Crop water use and total yield summary

Consumptive water use (m^3 ha^{-1}) was greatest in oca and lowest in pumpkin squash, whilst potatoes were intermediate, despite variation within cultivars (Appendix 4.4.1). The modern and heritage crops differed in their relationship between their maximum water requirement and actual evapotranspiration, thus crop coefficient (k_c) and maturity (Fig. 4.4.1). Taewa and Kamokamo used more water compared to modern cultivars (Table 4.4.2, Appendix 4.4.2). Green water was approximately 62%, 65%, 58% and 70% of consumptive water use, under irrigated modern potato, Taewa, pumpkin squash and oca, respectively. The dilution requirement (i.e the grey water) for the applied N in potato or oca and pumpkin squash had the equivalency of 425 m^3 ha^{-1} and 398 m^3 ha^{-1}, respectively (Table 4.4.2). Grey water increased in potato and oca compared to pumpkin squash, due to an increasing N rate.

Total yields amongst the eight cultivars were strongly influenced by water regime and cultivars, with yields showing a continuous increase, from rain-fed to irrigated condition, except in the case of Tutaekuri ($P<0.0001$), which ranged from 23.2 t ha^{-1} to 78.0 t ha^{-1} in irrigated fields and from 16.7 t ha^{-1} to 67.7 t ha^{-1} in rain-fed treatments. The greatest total yields were in Kamokamo, whilst the least total yields were observed in dark orange oca, under both water regimes ($P<0.0001$). The total yields for Kamokamo were significantly different from Agria, Buttercup squash, Moe Moe and Moonlight, which were not different between themselves, but different to Tutaekuri, scarlet oca and dark orange oca ($P<0.0001$). The total yield results demonstrated that scarlet and dark orange oca and Tutaekuri were the least in yields, out of the eight crop cultivars (Table 4.4.2). Partitioning to the harvested part was clearly demonstrated by the highest HI in Agria, followed by Moonlight and Moe Moe. The lowest HI was in oca cultivars, whilst pumpkin squash and Tutaekuri were intermediate. Heritage crop cultivars had extreme and relatively high vegetative biomass, compared to most modern cultivars in all the crops studied (Table 4.4.2).

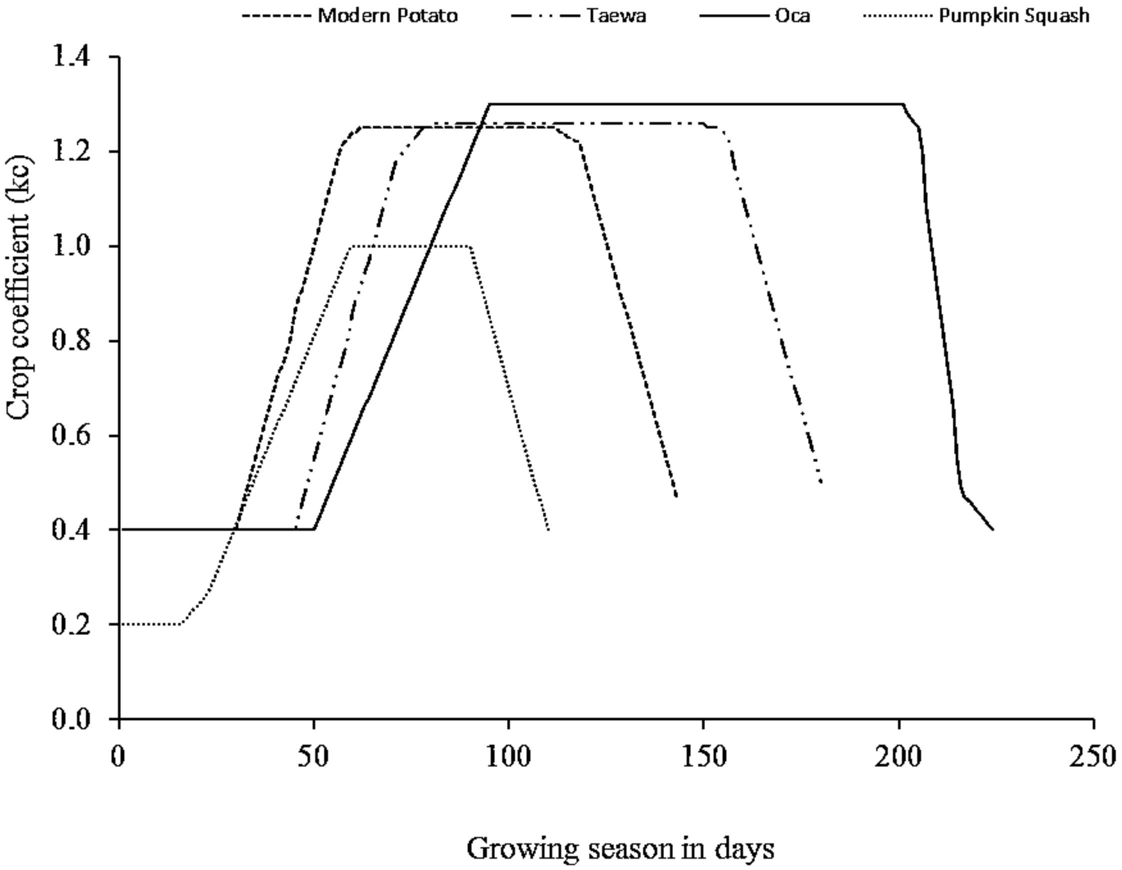


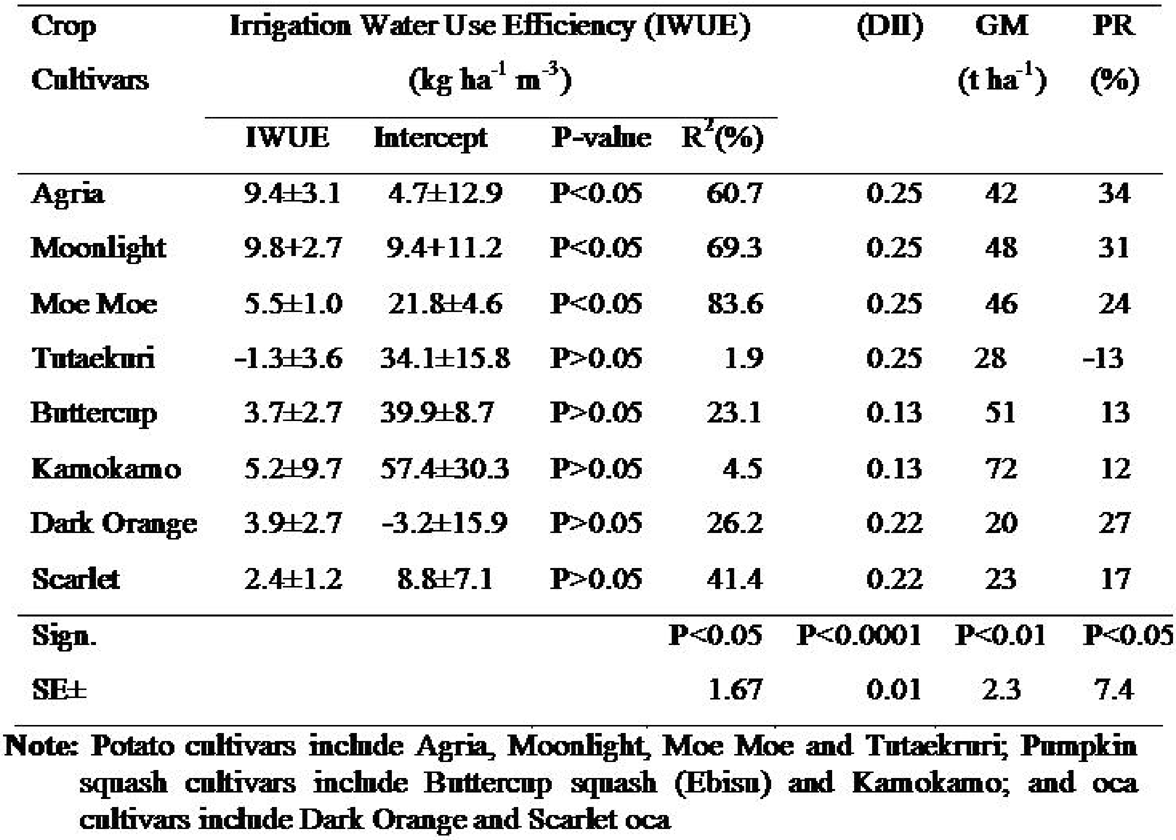
Figure 4.4.1 Crop coeficients and overlapping maturity period for modern potato, Taewa, oca and pumpkin squash, 2009/2010

4.3.4.3.2 Irrigation water use efficiency and water stress index

Irrigation water use efficiency (IWUE), geometrical mean (GM), drought intensity index (DII) and yield percentage reduction (PR) with water stress were significantly different between potato, pumpkin squash and oca cultivars, ($P<0.05$, $P<0.0001$, $P<0.01$, $P<0.05$), respectively (Table 4.4.1). The DII was significantly greater for potato than for pumpkin squash cultivars. However, all crop cultivars were below the severe water stress cut-off point of 0.7. The GM of the total yield was greatest in Kamokamo and least in dark orange oca ($P<0.0001$). The yield percentage reduction showed that total yield for Agria, Moonlight and dark orange oca were heavily affected by water stress, whilst Tutaekuri yield was not affected by water stress. Irrigation WUE was highest in plants which were more sensitive to water stress (Table 4.4.1).

Potato cultivars (except Tutaekuri) as measured by IWUE significantly responded to irrigation application ($P<0.05$; $P<0.01$; $P<0.05$). Moonlight was the most responsive potato cultivar to irrigation, with a total tuber yield increase of 9.8 kg ha^{-1} m^{-3}, followed by Agria (9.4 kg ha^{-1} m^{-3}) and Moe Moe (5.5 kg ha^{-1} m^{-3}). Tutaekuri decreased total tuber yield by 1.3 kg ha^{-1} m^{-3} with irrigation. The two pumpkin squash and two oca cultivars were almost intermediate. Kamokamo was the most responsive pumpkin squash cultivar, with a yield increase of 5.2 kg ha^{-1} m^{-3}, compared to Buttercup squash (3.7 kg ha^{-1} m^{-3}), as was dark orange oca (3.9 kg ha^{-1} m^{-3}) to scarlet oca cultivar (2.4 kg ha^{-1} m^{-3}). The results indicate that there is a linear relationship between total yield and crop water use in all eight crop cultivars (Table 4.4.1).

Table 4.4.1 Irrigation Water Use Efficiency (IWUE), Drought Intensity Index (DII), Geometrical Yield Mean (GM) and Percentage Reduction (PR %) of yield in heritage and modern crops cultivars, 2010



Crop Cultivars	Irrigation Water Use Efficiency (IWUE) (kg ha^{-1} m^{-3})				(DII)	GM ($t\ ha^{-1}$)	PR (%)
	IWUE	Intercept	P-value	R^2(%)			
Agria	9.4±3.1	4.7±12.9	$P<0.05$	60.7	0.25	42	34
Moonlight	9.8+2.7	9.4+11.2	$P<0.05$	69.3	0.25	48	31
Moe Moe	5.5±1.0	21.8±4.6	$P<0.05$	83.6	0.25	46	24
Tutaekuri	-1.3±3.6	34.1±15.8	$P>0.05$	1.9	0.25	28	-13
Buttercup	3.7±2.7	39.9±8.7	$P>0.05$	23.1	0.13	51	13
Kamokamo	5.2±9.7	57.4±30.3	$P>0.05$	4.5	0.13	72	12
Dark Orange	3.9±2.7	-3.2±15.9	$P>0.05$	26.2	0.22	20	27
Scarlet	2.4±1.2	8.8±7.1	$P>0.05$	41.4	0.22	23	17
Sign.				$P<0.05$	$P<0.0001$	$P<0.01$	$P<0.05$
SE±				1.67	0.01	2.3	7.4

Note: Potato cultivars include Agria, Moonlight, Moe Moe and Tutaekruri; Pumpkin squash cultivars include Buttercup squash (Ebisu) and Kamokamo; and oca cultivars include Dark Orange and Scarlet oca

4.3.4.3.3 Water footprint of growing heritage and modern crop cultivars

4.3.4.3.3 .1 Blue, green and grey water footprint on total yield basis

The green, blue and grey water footprint (WF) components varied with both crop cultivars and water regimes ($P<0.0001$), as presented in Tables 4.4.2. The consumptive WF (blue plus green WF or pure green WF) ranges were high in the irrigated field and low in the rain-fed field (Table 4.4.2). The average total consumptive WF increases with irrigation, from 140 to 155 (m^3 $tonne^{-1}$).

The total consumptive WF increased with irrigation in Moe Moe (9%), Tutaekuri (49%), Buttercup squash (34%), Kamokamo (34%) and scarlet oca (9%) whilst decreasing the total consumptive WF in Agria (2%), Moonlight (0%) and dark orange oca (5%) (Table 4.4.2). The cultivars with high IWUE had low WF under irrigated conditions, compared to rain-fed condition and vice versa (Table 4.4.1).

In the irrigated crops, the blue WF comprised 27 - 39%, whilst the grey WF made up to 6 - 9% of the total WF. The high yielding crops, per water unit, equaled low WF. All WF components were largest in dark orange oca and smallest in pumpkin squash, Kamokamo (Table 4.4.2).

4.3.4.3.3.2 Total water footprint of heritage and modern crop production

Total WF of growing potato, oca and pumpkin squash on total yield varied with crop cultivars ($P<0.0001$) and it ranged from 58 to 310 m^3 $tonne^{-1}$ under irrigation and from 46 to 335 m^3 $tonne^{-1}$ under rain-fed (Table 4.4.2). Dark orange oca had the largest average total WF, whilst pumpkin squash, Kamokamo, had the least ($P<0.0001$) (Figure 4.4.1; Table 4.4.2). The pumpkin squash cultivars and Moonlight were not significantly different on total WF, but they were different to Moe Moe, Agria, Tutaekuri and oca cultivars. Tutaekuri had the greatest total WF amongst the potato cultivars, although it was significantly lower than the oca cultivars ($P<0.0001$). Regardless of the crop water use increase with irrigation, the total WF between irrigation and rain-fed regimes were not statistically different ($P>0.05$).

Table 4.4.2 Consumptive and total water footprint of growing potato, oca and pumpkin squash crop cultivars on total yield (m^3 $ton.^{-1}$) in New Zealand, 2009/2010

Water regime/ Cultivars	Total Yield ($t\ ha^{-1}$)	HI (%)	Consumptive water use (m^3ha^{-1})			Grey water (m^3ha^{-1})	Consumptive WF (m^3 $ton.^{-1}$)			Grey WF	Total WF
			Green Water	Blue Water	Total CWU		Green WF	Blue WF	Total CWF		
Irrigation (n=16)											
Agria	51.7	88	3327	2000	5327	425	64	39	103	8	111
Moonlight	59.4	78	3256	2000	5256	425	54	34	88	7	95
Moe Moe	52.6	70	3685	2000	5685	425	70	38	108	8	116
Tutaekuri	27.6	50	3670	2000	5670	425	132	72	204	16	220
Buttercup	54.7	56	2326	1750	4076	398	43	32	75	7	82
Kamokamo	78.0	52	2382	1750	4132	398	30	22	52	6	58
Dark orange	23.2	43	4742	2000	6742	425	204	86	290	20	310
Scarlet	25.5	37	4824	2000	6824	425	189	78	267	17	284
Mean (n=32)	46.6	53	3527	-	5464	418	98	50	148	11	160
Rain-fed (n=16)											
Agria	34.0	78	3507	-	3507	425	103	-	103	13	116
Moonlight	39.7	78	3549	-	3549	425	90	-	90	11	100
Moe Moe	40.1	67	3986	-	3986	425	99	-	99	11	110
Tutaekuri	30.0	56	3969	-	3969	425	132	-	132	14	146
Butter cup	47.4	54	2587	-	2587	398	55	-	55	9	64
Kamokamo	67.7	47	2640	-	2640	398	39	-	39	7	46
Dark orange	16.7	41	5130	-	5130	425	307	-	307	28	335
Scarlet	21.2	42	5096	-	5096	425	245	-	245	21	261
Mean (n=32)	37.1	58	3808		3808	418	134		130	14	147
Significance											
Cultivars	$P<0.0001$	$P<0.001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	-	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$
Water Regime	$P<0.0001$	Ns	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	Ns
$LSD_{0.05}$											
Cultivars	10.7	6.7	-	-	-	-	44	10.7	51	4	55
Water Regime	5.4	-	-	-	-	-	22	5.3	18	2	27

4.3.4.3.4 Economic water productivity for modern and heritage crops

Economic water productivity (EWP), on a marketable yield basis, significantly differed between crop cultivars and water regimes ($P<0.0001$; Table 4.4.3). The rain-fed Agria, Moe Moe, Tutaekuri, Kamokamo and Buttercup squash had a greater water productive value than the irrigation treatments, whilst Moonlight had a greater EWP value under irrigation (Table 4.4.3). The oca cultivars' economic water productive value was similar between the two water regimes. The average EWP, per variety, shows that pumpkin squash, Kamokamo, had the greatest value per water unit under both water regimes (approximately 42.30 NZ$/m^3) and oca, especially dark orange oca, had the lowest EWP (approximately 4.40 NZ$/m^3).

Amongst the four potato cultivars, Moe Moe displayed a high EWP (approximately 33.50 NZ$/m^3), which was not significantly different from Ebisu (Buttercup squash), but it was significantly greater than other potato/oca cultivars and significantly lower than Kamokamo ($P<0.0001$) (Table 4.4.3). The two heritage cultivars, Kamokamo (pumpkin squash) and Moe Moe (potatoes), effectively outweighed the modern cultivars (Buttercup squash, Moonlight, Agria) in EWP (Table 4.4.3).

Table 4.4.3 Economic water productivity (NZ$) on marketable yield basis in heritage and modern crop cultivars under irrigation and rain-fed conditions

Water regime/ Cultivar	Water Use Efficiency (kg ha^{-1} m^{3})		Average Price (NZ$/kg)	Economic Water Productivity (NZ$/m^{3})
	Total Yield	Marketable Yield		
Irrigation				
Agria	10.3	7.2	1.43	10.30
Moonlight	11.7	8.8	1.43	12.50
Moe Moe	9.4	8.0	3.98	31.80
Tutaekuri	5.2	2.4	3.98	9.50
Buttercup	13.6	13.3	1.98	26.40
Kamokamo	19.7	17.6	1.98	34.90
Dark Orange	3.4	1.5	3.50	5.30
Scarlet	3.7	1.5	3.50	5.20
Mean (n=32)	9.6	7.5	2.72	17.00
Rain-fed				
Agria	10.9	7.8	1.43	11.20
Moonlight	12.9	7.9	1.43	11.30
Moe Moe	12.1	8.9	3.98	35.20
Tutaekuri	9.0	3.5	3.98	14.00
Buttercup	23.0	18.4	1.98	36.40
Kamokamo	34.2	28.1	1.98	49.70
Dark Orange	3.3	1.0	3.50	3.50
Scarlet	4.2	1.5	3.50	5.20
Mean (n=32)	13.7	9.6	2.72	20.80
Significance				
Cultivar	P<0.0001	P<0.0001		P<0.0001
Water regime	P<0.0001	P<0.0001		P<0.0001
LSD$_{0.05}$				
Cultivar	4.2	3.5		7.00
Water regime	1.2	1.0		2.10

Note: Crop prices are stated according to Statistics New Zealand, 2010 (http://www.stats.govt.nz); Osborne (2010) for New Zealand yam (oca); Taewa price was from Pak & Save Palmerston North and Roskruge (Personal communication, 2010).

4.3.4.4 Discussion

4.3.4.4.1 Crop water use and total yield production

Modern and heritage crops differ in their relationship between their maximum water requirement and actual evapotranspiration, thus crop coefficient (k_c), in addition to maturity. Figure 4.4.1 shows how the crop coefficient (or growing stages) overlapped during the growing season. The actual implementation of irrigation may result in over-irrigating pumpkin squash in order to meet the water requirements of other crops. It was discovered that differences in growth stages and maturity, between crops and within potato cultivars (Taewa and modern potato), created disparities in their water requirements (Allen *et al.,* 1998). Taewa and oca have an extended crop development time and mid-stages and (as a result) these are the stages that are generally affected by drought according to volumetric soil moisture, whereas their later stage is frequently affected by frost, especially oca.

The volumetric soil moisture indicates that the fully irrigated treatment maintained the soil water content within the available water level, which is regarded as critical for maximum yield in many crops (Ferreira *et al.*, 2007). In contrast, the rain-fed treatment did not fully balance the water required by the plants and as a result the plants extracted more stored water from the soil profile. The heritage cultivars (Kamokamo and Moe Moe) managed to extract more water than their counterparts under water deficit conditions. The majority of the heritage crop cultivars used more water than the modern cultivars. It is probable that the longer growth cycle in heritage crop cultivars (Kamokamo, Taewa and oca) resulted in them using more water than the modern cultivars. The crop evapotranspiration results provide a benchmark for the water requirements of heritage and modern crop cultivars of potato, oca and pumpkin squash in New Zealand (Appendix 4.4.1). Perfomance of Kamokamo and Moe Moe signified their capacity to survive limited water conditions.

The increases in yield components, with the use of irrigation, measured in this study, broaden previous observations that irrigation improves potato yields (Ferreira *et al.*, 2007) and pumpkin squash yields (Al-Omran *et al.,* 2005; Morgan *et al.,* 2003). However, the effect of irrigation on oca yields has not been reported. In this study the rain-fed oca yields were greater than those reported in the Andean region (Bormejo *et* *al.,* 1994) and yet, the yield were within those reported in New Zealand (Martin *et al.,* 1999), while the irrigated oca yields were above normal average yields (King, 1987). The overall analysis shows that, amongst the crop cultivars studied, other heritage cultivars (Kamokamo and Moe Moe) produced relatively more than expected, when compared to modern crop cultivars (Table 4.4.2).

4.3.4.4.2 Irrigation water use efficiency

The total and marketable yields of all the crop cultivars studied were responsive to water supply, except for Tutaekuri. Water stress reduced the total yields of rain-fed crops to 34%, 31%, 24%, 13%, 12%, 27%, 17% of irrigated Agria, Moonlight, Moe Moe, Buttercup squash, Kamokamo, Dark Orange and Scarlet oca, respectively. Comparatively, the combination of low yield reduction and high GM in Kamokamo indicates that it is physiologically better at transforming water to carbon, compared to the root and tuber crops studied. High GM and low DII and PR in Table 4.4.1 are indices for selecting crops that are tolerant to environmental stress (de Souza Lambert *et al.,* 2006). Noticeably, Kamokamo had a high yield potential, compared to all other crop cultivars, under both environments. However, IWUE was high in modern potato (Moonlight and Agria), whilst Kamokamo was comparable to Moe Moe, Buttercup squash and Dark Orange IWUE, despite its high yield potential.

Modern potato almost doubled IWUE, compared to Kamokamo, Moe Moe, Buttercup squash and Dark orange oca. Similarly, the yield reduction reflects that the modern potato was very sensitive to water stress (Shock *et al.,* 2007), compared to the heritage potato, pumpkin squash and Scarlet oca. In spite of this fact, the yield reduction of potato was less than that documented by Ferreira *et al.* (2007), thus confirming that the yield reduction was moderate. Potentially, the modern potato cultivars and Dark Orange oca could reduce their yield beyond this stage, with DII over 0.7 (Ramirez-Vallejo *et al.,* 1998). The IWUE in potato shows that it varies with genotype, such as Tutaekuri, which does not respond to water application, possibly due to species differences and low HI. The moderately poor IWUE of Tutaekuri confirms the previous glasshouse trial results, which found that Tutaekuri was unresponsive to 100 % ET, due to the same reasons (Chapter 3).

4.3.4.4.3 Water footprint of growing heritage and modern crop production

Water footprint components differed with crop type or cultivars and water regimes, which have also been reported in various energy crops (Gerbens-Leenesa *et al.,* 2009b). Pumpkin squash, Kamokamo, was the most efficient crop cultivar, whilst Dark Orange oca was the least efficient crop, on a water productivity basis (Fig. 4.4.1). The total water footprint of pumpkin squash cultivar was comparable to Moonlight, but it was almost five times smaller than WF of growing oca. Similarly, Moonlight, Agria and Moe Moe had comparable benefits on WF, compared to Tutaekuri; where the WF was double that of other potato cultivars. Tutaekuri and pumpkin squash cultivars were more beneficial under rain-fed than irrigation. Otherwise, no advantage was identified for growing oca, except in the case of a promising premium price, which would counteract low water productivity, compared to potato and pumpkin squash.

The average total WF, which varied with cultivar, ranged from 46 m^3 ton^{-1} to 335 m^3 $tonne^{-1}$. A comparison of the WF of producing potato with results reported in the Netherlands (72 m^3 $tonne^{-1}$), USA (111 m^3 $tonne^{-1}$), Brazil (106 m^3 $tonne^{-1}$) and Zimbabwe (225 m^3 $tonne^{-1}$) (Gerbens-Leenes *et al.*, 2009b), shows that the water footprint of all four potato cultivars was greater than that for the Netherlands and almost equal to USA and Brazil, except for Tutaekuri, which was equal to the WF of growing potato in Zimbabwe. Furthermore, this study shows that the water footprint for producing potato and pumpkin squash in New Zealand is either within, or smaller than that of crops with the smallest water footprints in referred regions. Oca, which had the largest total water footprint in this study, is within the range of crops with the smallest water footprints: sugar beet, sugarcane and maize, reported in Netherlands, USA, Brazil and Zimbabwe (Gerbens-Leenesa *et al.,* 2009b).

The average WF of growing Agria, Moonlight, Moe Moe, Tutaekuri, Buttercup squash, Kamokamo, dark orange and Scarlet oca, correspondingly relates to 12, 10, 11, 20, 7, 5, 35 and 28 *l* of virtual water content, in order to produce 100g. The virtual water content for potato and pumpkin squash is lower than the 25*l*/100g for potato tuber (Hoekstra *et al.*, 2007) and the 23.8*l*/100g for pumpkin (Kumar *et al.*, 2007), which were estimated as mean global and Indian virtual water content, respectively. The virtual water content to produce oca was greater than the 25*l*/100g for potato tuber. The average WF of this study is also smaller, compared to the 1995 - 2006 global WF of pumpkin squash (336 m^3 $tonne^{-1}$) and potato (287 m^3 $tonne^{-1}$.) (Mekonnen *et al.,* 2010b).

The results suggest that there are great disparities in virtual water content and WF within global averages, which may be due to climate, cultivars and methodological differences, when estimating crop water use (Kumar *et al.,* 2007; Hoekstra *et al.,* 2007). This study used actual water use and actual yield, as suggested by Maes *et al.* (2009), whilst the study referred to used hypothetical crops and water (Gerbens-Leenes *et al.,* 2009a). On the other hand, the virtual water content and WF, in this study, outweigh the global WF put forward by Mekonnen *et al.* (2010b), where actual water use was used, thus proving some level of sparing water use, compared to other parts of the world. These attributes could be due to efficient agricultural practices, crop cultivars and good weather patterns in this particular study and year as formerly suggested by Hoekstra *et al.* (2007).

From the irrigated crops, it was apparent that blue water increased total crop water use by 34%, 48% and 59%, in oca, potato and pumpkin squash cultivars, respectively. As a consequence, blue water evidently raised the total water footprint of the total yield in Moe Moe, Tutaekuri, Buttercup squash, Kamokamo, and Scarlet oca by 5%, 45%, 28%, 25% and 8%, as also reported in wheat, whilst reducing the total water footprint of total yield in Agria, Moonlight and dark orange oca by 6 %, 4% and 7%, as also reported in sugarcane and soybean, respectively (Mekonnen *et al.,* 2010b). Irrigation was essential in reducing the total WF, by increasing total and marketable yields, especially in crop varieties that were very responsive to irrigation or sensitive to water stress. However, irrigation increased actual evapotranspiration and nearly potential evapotranspiration in Moe Moe, Tutaekuri, Buttercup squash, Kamokamo, and scarlet, despite increasing a yield that raised their total WF. This highlights that irrigation is indispensable for yield quality improvement in crops with high IWUE and when rainfall is limited for most modern crops (Fabeiro *et al.,* 2001; Kang *et al.,* 2002) and some heritage crops, such as Moe Moe and oca.

4.3.4.4.4 Economic water productivity

The EWP was highest under limited water, except with Moonlight. Battilani *et al.* (2004) and Zoebl (2006) also reported that crop water productivity was higher in rain-fed than in well watered crops. In this study, Moonlight shows that its EWP was not limited to increased water allocation, due to its high IWUE reported previously. However, the average value obtained, per unit of water allocated to different crops, was greatest in Kamokamo and Moe Moe, due to their large yield and high market value. In this case, EWP is related to crop yield potential and market prices and other related water management factors (Molden *et al.,* 2001).

The average economic water productivity values in equivalent to 20.4 US\$/m^3 (2.70 to 38.10 US\$/m^3) are twenty-fold those reported in 23 irrigated crops in Asia, Africa and Latin America, with a range of 0.03 to 0.91 US\$/m^3 (IWMI, 2002). Potato has been reported to have 0.3 US\$/m^3 in Jordan (Molden *et al.,* 2001; FAO, 2003). These findings confirm a great spatial variation in economic water productivity between and within crops and regions, due to variations in crop management, market value and weather (Kumar *et al.,* 2007; Hoekstra *et al.,* 2007).

Adoption of the information on IWUE, WF and EWP for various crops under rain-fed and irrigation regimes can help growers to allocate water more efficiently. The selection of cultivars can be based on IWUE, EWP and WF for particular water regimes or technology available (Hoekstra *et al.,* 2009). Irrigation water use efficiency and EWP indicate that modern potato has a comparative advantage under irrigation, than pumpkin squash, Moe Moe, and Tutaekuri under rain-fed. However, irrigation is very essential for Moe Moe, oca and pumpkin squash for increased marketable yield and income and for a reduction in unanticipated drought risk and poverty (SIWI *et al.,* 2005).

4.4 Summary and Conclusion

The field study indicates that irrigation influences total yield, marketable yield production and values of WF and EWP, for both heritage and modern crop cultivars differently, depending on their water extraction capacity, their ability to transform water to carbon and how they partition these assimilates to economic organs. The majority of heritage cultivars extract and synthesise more total assimilates. However, they prioritise allocation of assimilates to vegetative growth, compared to modern cultivars that optimise partitioning of assimilates to the harvestable part.

This study also suggests that pumpkin squash has the highest yield potential and economic water productivity, due to its ability to use water efficiently within a short lifespan, whereas Moe Moe is the potato highest EWP, due to its premium market value and its ability to modify harvest index with irrigation application. It was also observed that the modern potato is recommended more for irrigation, compared to pumpkin squash and Tutaekuri, due to their high IWUE and sensitivity to water stress. This indicates that where water is limited, selection of crops should be based on high yield potential, plus EWP and low WF (as noticed in Kamokamo and Moe Moe), or optimisation of irrigation water should be based on crops that have a high IWUE (as observed in modern potato). Other crop cultivars did not need irrigation even when water was limited, due to their hereditary makeup (as observed in Tutaekuri). Others need irrigation due to their long lifecycle, which was affected by weather variability (as observed in oca). Consequently, the growers’ final choice of enterprise needs to be based on a combination of market demand, crop water productivity and water availability.

CHAPTER 5

COMPARISON IN THE FIELD OF YIELD AND WATER USE EFFICIENCY OF TAEWA AND A MODERN POTATO CULTIVAR

5.1 Introduction

The results of the glasshouse experiment described in Chapter 3 and the field experiment described in Chapter 4 established that Moe Moe, one of the Taewa cultivars, responded to full irrigation and it competed favourably with modern potato cultivars, in tuber yield and WUE. In contrast, Tutaekuri (*S. andigena*) did not respond to full irrigation compared to its counterpart, Moe Moe. Tutaekuri's poor response to irrigation was unexpected because potatoes usually respond to irrigation, perhaps due to specie difference (Bowen, 2003; Kang *et al.,* 2004; Shock *et al.,* 2007). Subsequently, it was assumed that a low N and partial irrigation would interactively stimulate Tutaekuri to perform in the same way as Moe Moe and modern cultivars, under irrigation. This assumption is based on the fact that modern cultivars are bred for high yield, WUE and NUE while old or wild cultivars have low WUE and NUE because they were self-selected for adverse condition (Zebarth, *et al.,* 2008; Siddique *et al.,* 1990a).

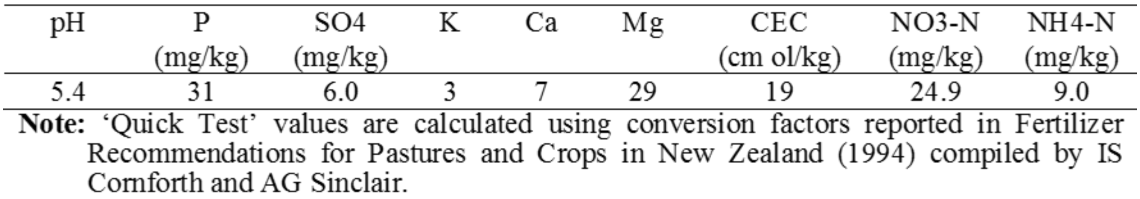
Irrigation and N enhance modern potato tuber yields and tuber quality (Shock *et al.,* 2007). Presently, studies show that 200 - 300 kg N ha^{-1} with 500 - 700 mm of water is the best rate for modern potato production in New Zealand (Craighead *et al.,* 2003). 200 - 250 kg N ha^{-1} is recommended for short season crops and 300 kg N ha^{-1} for long season crops. Hayward (2002) undertook a preliminary study of the effect of N on Taewa yield and this study indicated that there was no yield response to an increase in N. Given that the response of potato to soil moisture and N use is mainly influenced by genotypes (Laurence *et al.,* 1985; Steyn *et al.,* 1998), N and water application need to be matched to Taewa growth habits, or otherwise their yield will not improve. Significant differences in tuber yields, between Taewa and modern cultivars, have been reported by Harris *et al.* (1999) and chapter 3 and 4. However, studies of Taewa have not considered irrigation and N concurrently in the field. Consequently, a field experiment was conducted, in order to determine the effect of irrigation and N regimes on vegetative growth, dry matter partitioning, photosynthetic WUE, tuber dry matter and SG characteristics, N leaching, tuber yield, WUE and NUE in Taewa, in comparison with the modern cultivar, Agria, in the field.

5.2 Material and Methods

5.2.1 Experimental site

The field experiment was conducted at Massey University's Pasture and Crop Research Unit, Palmerston North, New Zealand. It was planted on 27th October 2010 and harvested on 16th April, 2011. The soil is a Manawatu sandy loam soil. The detailed soil chemical characteristics, at the beginning of the experiment, are presented in Table 5.1. The soil samples were analysed at Massey University's Fertilizer and Lime Research Centre. Total available N was <30 kg N ha^{-1}. The maximum and minimum temperature, cumulative evapotranspiration and rainfall (mm) for the site during the October 2010 to April 2011 season are presented in Figure 5.2.

Table 5.1 Soil chemical properties at the beginning of experiment, October, 2010

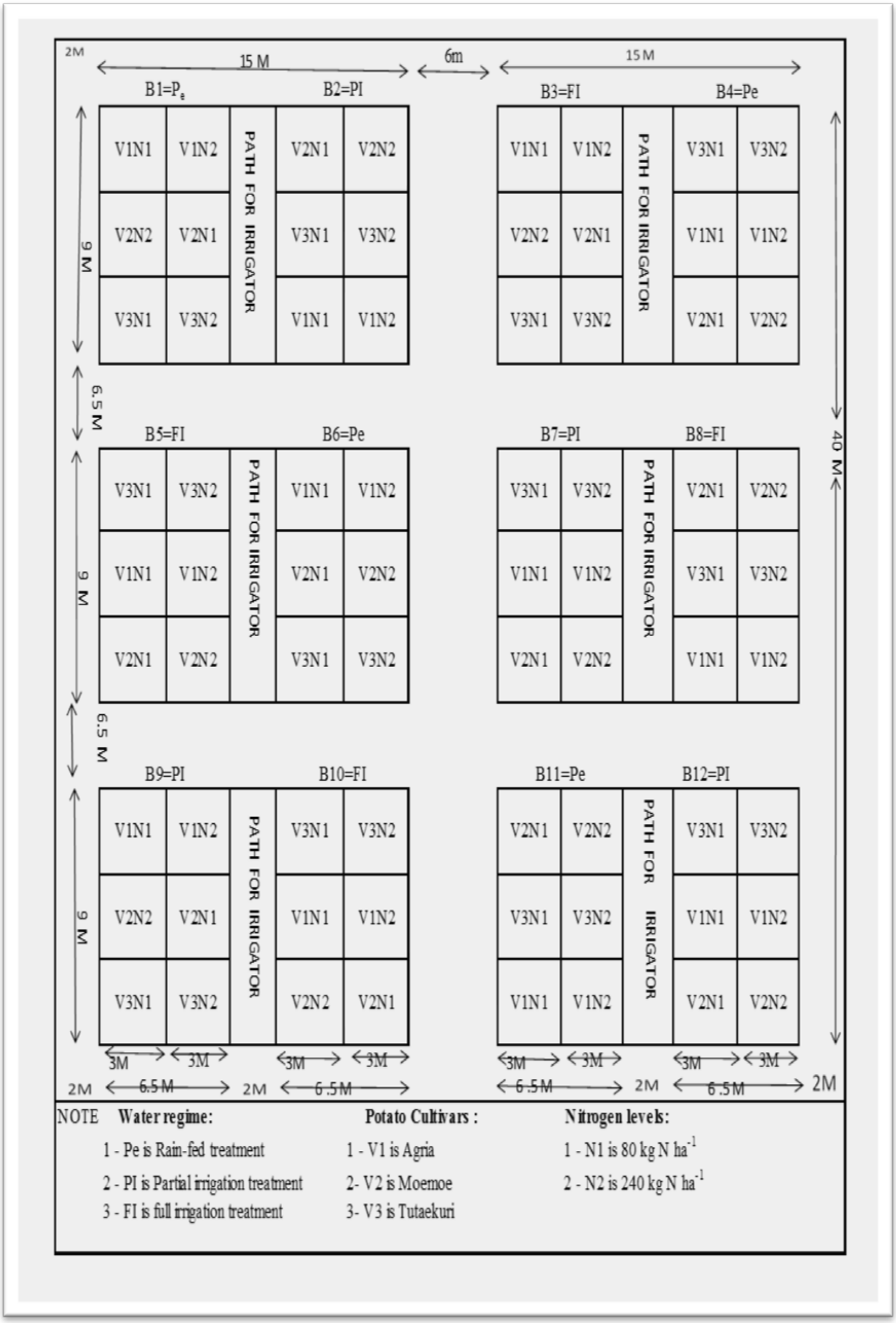


pH	P (mg/kg)	SO4 (mg/kg)	K	Ca	Mg	CEC (cm ol/kg)	NO3-N (mg/kg)	NH4-N (mg/kg)
5.4	31	6.0	3	7	29	19	24.9	9.0

Note: 'Quick Test' values are calculated using conversion factors reported in Fertilizer Recommendations for Pastures and Crops in New Zealand (1994) compiled by IS Cornforth and AG Sinclair.

5.2.2 Experimental design and treatments

The field experiment was a Randomised Incomplete Block Split-Split-Plot Design (RIBD Split-Split-Plot) with three water regimes as the main treatments, three potato cultivars (Agria, Moe Moe and Tutaekuri) as sub-treatments and two N levels of N1=80 and N2=240, as sub-sub-treatments; this was replicated four times (Figure 5.1). The three water regimes were (1) rain-fed (P_e); (2) partial irrigation (PI); and (3) full irrigation treatment (FI). The FI received 25 mm irrigation at 30 mm soil moisture deficit (SMD), from plant emergence to crop physiological maturity. Irrigation was not applied to the PI treatment at the first irrigation of the FI treatment and was then irrigated at every second irrigation of FI.



NOTE **Water regime:**
1 - Pe is Rain-fed treatment
2 - PI is Partial irrigation treatment
3 - FI is full irrigation treatment

Potato Cultivars :
1 - V1 is Agria
2- V2 is Moemoe
3- V3 is Tutaekuri

Nitrogen levels:
1 - N1 is 80 kg N ha^{-1}
2 - N2 is 240 kg N ha^{-1}

Figure 5.1 Schematic diagram for the field layout of Experiment 3 for irrigation and nitrogen treatments of Taewa and modern potato cultivars

5.2.3 Irrigation and crop management

5.2.3.1 Fertiliser and plant protection

The potatoes received 12N:5.2P:14K: 6S+2Mg+5Ca, using 500 kg ha^{-1} Nitrophoska Blue TE at planting. All plots received the same amount of fertiliser at planting and this was followed by 20 and 180 kg N ha^{-1} of urea (as a side dressing) on 10th December, 2010, in treatment N1 and N2, 24 days after emergence, respectively. Mounding was undertaken following the side dressing on 10th December, 2010, by using a tractor to embank the crop and control weeds. Herbicides were not used to control weeds and secondary weeds were manually controlled.

Avermectin B1a (Avid or abamectin) and imidacloprid chloro-nicotinyl 700 g/kg (Confidor 70WG) were sprayed interchangeably every 10 - 14 days, in order to protect the potato from sucking and biting insect pests: leaf suckers and leafhoppers (*Empoasca fabae*), mites, and potato psyllid (*Bactericera cockerelli*) (Appendix 7.3). Chlorothalonil Tetrachloroiophthalonitrile (Bravo ULTREX SDG90), a broad spectrum fungicide, was sprayed to control fungal (late blight, *Phytophthora infestans*) and bacterial diseases, together with Avid and Confidor. A number of plants displayed potato psyllid symptoms (psyllid yellows) and presence of psyllid eggs, adult psyllids and pysllid nymphs underside leaf after 110 and 140 days after plant emergence (Roskruge, 2011 Pers comm.). Consequently, all the plants infested were visually scored for severity of symptoms and presence of any form of psyllid, on a scale of 0 – 5, where, 0 is for no infestation and 5 for highly infested plots (Table 5.3). Potato psyllid were identified according to Roskruge *et al.* (2010).

5.2.3.2 Irrigation scheduling and irrigation depth

Full irrigation treatment received 25 mm irrigation at 30 mm SMD, between 4th December, 2010 and 20th March, 2011. Full irrigation plots received seven irrigations, whilst PI plots received three irrigations. Irrigation was applied with a Trail boom traveller irrigator (Plate 5.2a) and crop water use for irrigated and rain-fed treatments was determined by the soil water balance approach (Allen *et.al.*, 1998), whilst soil moisture measurements were taken by TDR [model 1502C, Tektronix Inc., Beaverton, OR, USA], as described in Chapter 4. The actual water distribution within each plot was monitored (at every irrigation) by using a number of catch cans. The catch cans were laid longitudinally at 0.5 m apart. At the end of the irrigation period, water trapped in the cans was measured and recorded. The irrigation depth for a particular plot was determined as an average of the water depth in the catch cans from each plot.

5.2.4 Plot size and plant spacing

Potato tubers were manually planted on 27th October, 2010, at 75 cm spacing between rows and 30 cm spacing within rows, at a depth of 10 - 15 cm. Each plot was 3 m by 1.5 m, containing 18 plants, and contained two guard rows planted with the same potato cultivar, except Tutaekuri, where Moe Moe was used as guard crop, due to insufficient seed potatoes (Figure 5.1 and Plate 5.1b).

5.2.5 Growth morphological and gaseous exchange characteristics measurements

Vegetative growth characteristics were measured on plant height (cm); number of stems per plant; number of branches per plant; and stem diameter at soil collar (mm), 120 days from planting. Gaseous exchange was measured once, at 90 DAE, using CIRAS-2, which is a portable photosynthesis system (V2.01), described in chapter 3. Photosynthetic WUE (μmolCo$_2$/m molH$_2$O) was determined as the ratio of net photosynthesis to transpiration rate as described in chapter 3 (Liu *et al.*, 2006a) (Plate 5.1a).

(a) Gaseous exchange measurements by CIRAS - 2

(b) Leaf water potential measurements by Pressure chamber

Plate 5. 1 Gaseouse exchange and Leaf water potential measurements

Leaf water potential (Ψ_w) was measured using the Scholander pressure chamber method [Soil Moisture Equipment Corp., Santa Barbara, CA, USA] on both irrigated and non-irrigated plants (Boyer 1995). Leaf water potential was measured in the morning (6:00-8:00 am) at the development crop stage (Plate 5.1b).

Above-ground (leaves and stems) and below-ground biomass (roots and tubers) were sampled between 14th and 18th February 2011, which was 120 days after planting. A small and a large plant sample were randomly uprooted from each plot, by using a spade. The plants were thoroughly washed, and then partitioned into leaves, stems, roots and tubers and weighed and oven dried at 70°C, until there was no further weight loss. The contribution of each component to total biomass was determined as the ratio of each component to total biomass (leaves, stems, roots and tubers), per plant. Root : shoot ratio was determined as dry weight for roots divided by the dry weight of the above-ground biomass (leaves +stems biomass) (Siddique *et al.,* 1990b). Harvest index was calculated 120 DAP, as the ratio of total tuber yield to total biomass production from the samples of each plot (Mackerron *et al.,* 1985). Detailed procedures for vegetative growth, dry matter production and partitions per plant, and gaseous exchange characteristic measurements are described in Chapters 3 and 4.

5.2.6 Soil water sampling procedure for nitrogen leaching measurements

In a very preliminary measure of N leaching, soil water samples were collected from the 24 plots of FI and 24 plots of rain-fed treatments, during summer and winter season. Half of the plots in each water regime received high N, whilst the other half received low N for all three potato cultivars. Nitrogen leaching was monitored using forty-eight porous ceramic suction cup samplers (Curley *et al.,* 2011). These cups were 75 mm long and 22 mm in diameter, cemented onto a 22 mm outside diameter PVC pipe, 60 cm in length. The porous ceramic suction samplers were installed at a depth of 30 cm in holes made by a soil auger at the middle of each plot, one week after planting. The suction cups and soil media hydraulic contact and stability were enforced by slurry from the augured soil before and after inserting the suction probe. PVC cups were used to close the PVC end.

A manual vacuum pump made from high quality material was used to create a vacuum in samplers, 24 - 48 hrs before sampling. The vaccum was maintained with a rubber stopper. After 24 - 48 hrs, the soil water in the PVC tubes was siphoned with a 50 ml syringe connected to a length of polythene tube. The siphoned samples were transferred into a well tagged plastic flask, which was stored frozen, prior to laboratory analysis. Sampling was conducted on several occasions during irrigation and after heavy rain.

Laboratory analysis was conducted on the ammonium-N ($NH4^+$-NO_3) and nitrate-N (NO_3-N) content, by using a Technicon II Auto-Analyser (the Ammonium-Nitrate procedures) at the Fertilizer and Lime Research Centre (FLRC) within the Institute of Natural Resources, Massey University, Palmerston North (Technicon, 1976; Downes, 1978). Nitrate-N leaching was estimated per ha by multiplying the Nitrate-N concentration of soil water samples by the drainage volume estimated using the soil water balance (Sumanasena, 2003).

5.2.7 Tuber yield and biomass production measurements

5.2.7.1 Total tuber yield, marketable tuber yield and final harvest index

The potatoes were finally harvested on 16th April, 2011 using a potato harvester. At harvest, the total fresh tuber yield per plot (kg), marketable tuber yield per plot (kg), number of tubers per plant, and average tuber weight per plant were measured. Marketable tubers were those weighing above 55 g, without any damage while small, damaged tubers were categorized as non-marketable. Marketable potato tubers were not graded further (Plate 5.2cd). Final HI was calculated, described in Chapter 4 (Mackerron *et al.*, 1985).

5.2.7.2 Water use efficiency indicators and statistical analysis

Water use efficiency, economic water productivity, irrigation water use efficiency and water stress indicators were determined (Chapter 4). The data collected were analysed with the GLM procedure of the SAS (SAS, 2008), differences amongst treatment means were compared with the LSD, at the 5% probability level (Meier, 2006). The relationship between water use and tuber yield was investigated using regression analysis (Ferreira *et al.,* 2007).

The RIBD Split-Split-plot linear statistical model used in GLM procedure was:

$$\yen ijk = \mu + \hat{I}_i+\beta_j+(\hat{I}\beta)_{ij}+\alpha_k+(\hat{I}\alpha)_{ik}+(\beta\alpha)_{jk}+(\hat{I}\beta\alpha)_{ijk}+\boldsymbol{\Omega}_{\ell}+(\hat{I}\alpha\Omega)_{ik\ell}+\hat{I}\beta\alpha\Omega)_{ijk\ell}+\text{Ę}_{ijk\ell};$$

Where, μ is the overall mean; $\hat{I}_i$, β_j, $(\hat{I}\beta)_{ij}$ represents the whole plot as water regimes, block and whole plot error effects; α_k, $(\hat{I}\alpha)_{ik}$, $(\beta\alpha)_{jk}$ represents subplots as potato cultivars effects, block effects and subplot errors; $(\hat{I}\beta\alpha)_{ijk}$ represents whole plot and subplot interaction effects; $\boldsymbol{\Omega}_{\ell}$, $(\hat{I}\alpha\Omega)_{ik\ell}$, $\hat{I}\beta\alpha\Omega)_{ijk\ell}$ represents the sub-sub plot as N, block effects and sub-sub plot errors; whole plot, subplot and sub-sub-plot interaction and $\text{Ę}_{ijk\ell}$ represents overall error, respectively, whilst i= 1-3 water regimes, j=1-4 replicates, k=1-3 potato cultivars, $\boldsymbol{\ell}$=1-2 represents N levels.

(a) Travel irrigator irrigating Taewa

(b) Outlook of irrigated modern and heritage potato in the field in 2010/2011 season

(c) Graded Moe Moe

(d) Graded Tutaekuri

Plate 5.2 Outlook of irrigated Moe Moe and Tutaekuri potatoes in 2010/2011 season

5. 3 Results

5.3.1 Crop evapotranspiration and soil moisture content

5.3.1.1 Cumulative potential evapotranspiration, precipitation, and mean temperature

The growing seasons for Taewa and modern potato were 170 and 140 days, with potential crop water requirements of 611 mm and 491 mm, respectively (Table 5.2; Fig. 5.2). Seasonal precipitation of 368 mm contributed 50 - 60% of the total crop water requirement (Fig.5.2). The average maximum and minimum temperatures, total solar radiation and average wind speed for the 2010/2011 season were 24.9°C, 9°C, 3395 (MJ/m^2) and 291 (km day^{-1}), respectively.

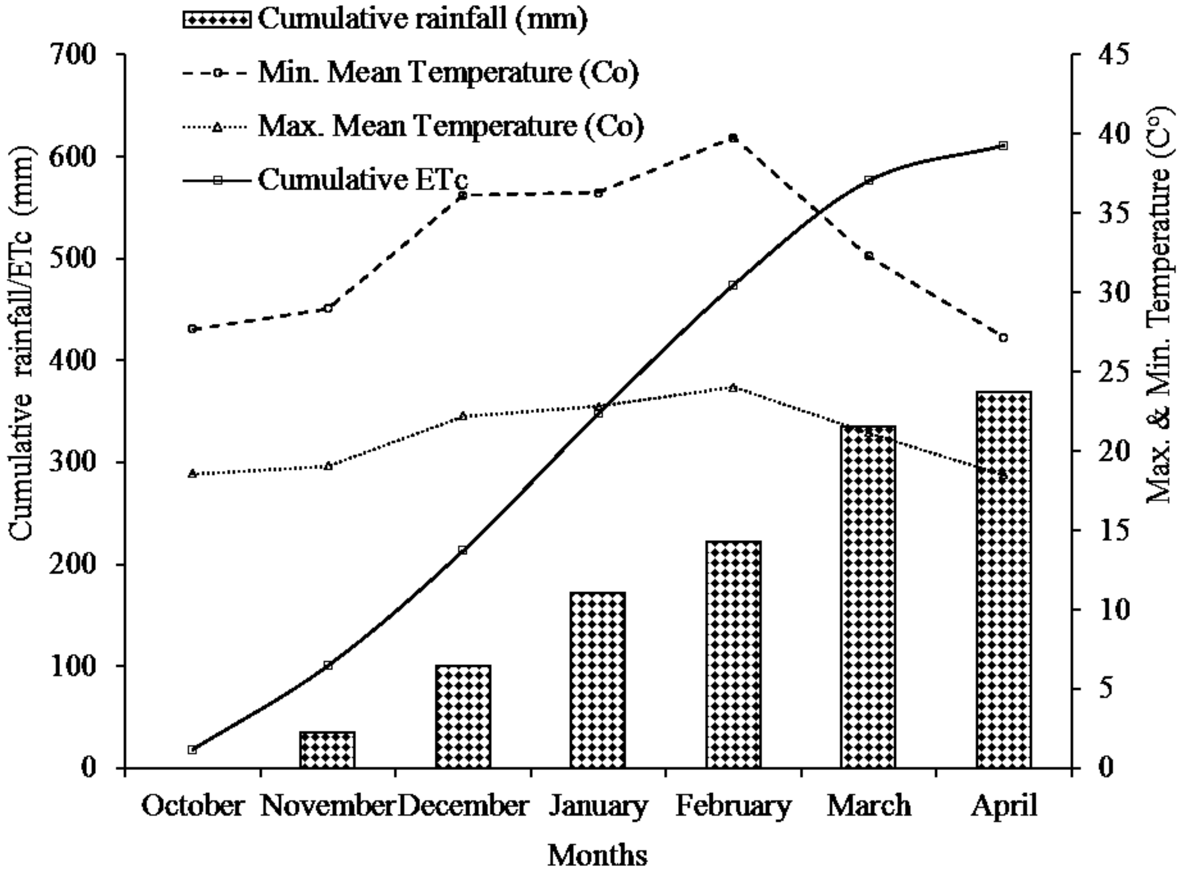


Figure 5.2 Cumulative rainfall (mm), potential crop evapotranspiration (mm), monthly average maximum temperature and minimum temperature (°C) for the experimental site during the growing season from October, 2010 - April, 2011

5.3.1.2 Actual crop water use per irrigation scheduling

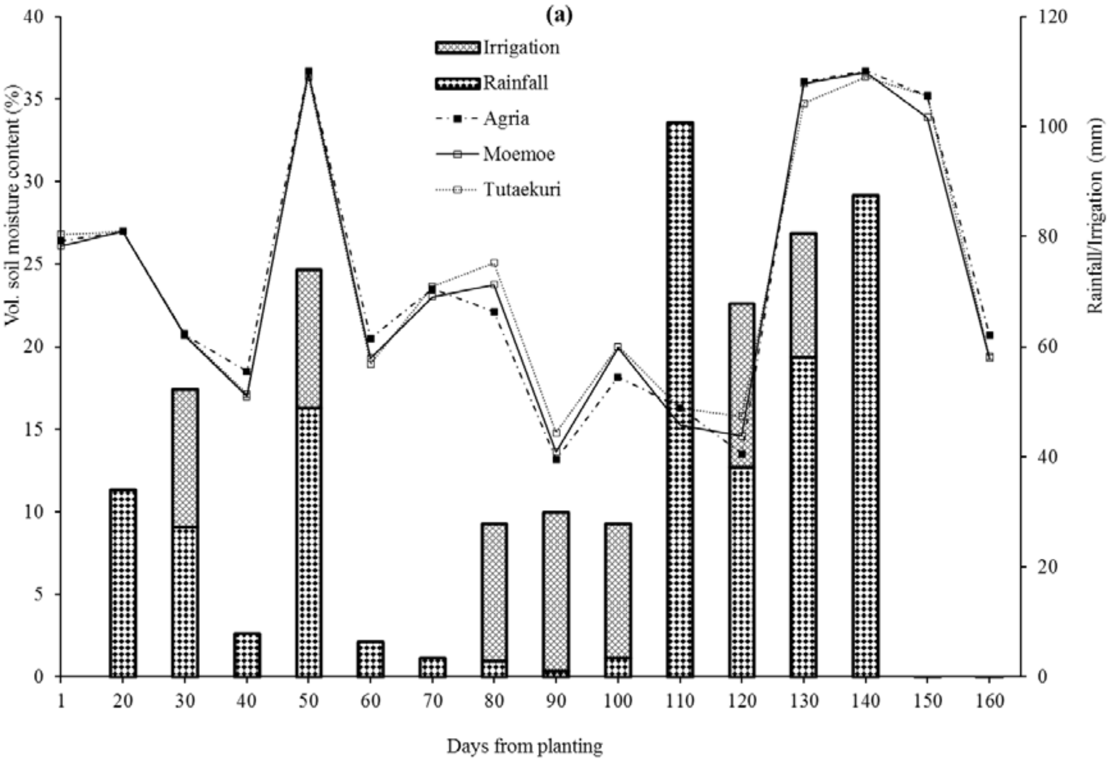
The actual evapotranspiration for the full irrigation (FI), partial irrigation (PI) and rain-fed treatments (P_e) averaged 523.4, 416.4 and 355.6 mm, respectively (Table 5.2). Full irrigation and PI were irrigated seven and three times, respectively. The water use for FI, PI and P_e treatments was 92%, 73% and 60% of potential water requirement, respectively ($P<0.0001$). Consumptive water use (m^3 ha^{-1}) was greatest in FI and lowest in rain-fed treatment (Pe), whilst PI was intermediate. Taewa used more water compared to the modern cultivar, Agria (Table 5.2, Appendix 5.1b).

Table 5.2 : Precipitation (P_e); irrigation (I); deep percolation (D_p); soil moisture change (ΔS); actual evapotranspiration (ET_c); and crop water use [ETc or CWU = $Pe + I – D_p + \Delta S$] from 27th October, 2010 to 12th April, 2011

Water regime/ Cultivars	P_e (mm)	I (mm)	D_p (mm)	ΔS (mm)	ETc (mm)	CWU ($m^3 ha^{-1}$)
Full irrigation						
Agria	280	180	13.3	17.6	464.3	4643
Moe Moe	368	180	13.3	19.4	554.1	5541
Tutaekuri	368	180	13.3	17.2	551.9	5519
Mean	338.7	180	13.3	18.1	523.4	5234
Partial irrigation						
Agria	280	75	13.3	16.9	358.6	3586
Moe Moe	368	75	13.3	15.0	444.7	4447
Tutaekuri	368	75	13.3	16.1	445.8	4458
Mean	338.7	75	13.3	16.0	416.4	4164
Rain-fed						
Agria	280	0.0	0.0	16.2	296.2	2962
Moe Moe	368	0.0	0.0	17.7	385.7	3857
Tutaekuri	368	0.0	0.0	16.4	385.1	3851
Mean	338.7	0.0	0.0	16.6	355.6	3556

5.3.1.3 Volumetric soil moisture content (%)

Soil moisture content was significantly influenced by cultivar ($P<0.01$), irrigation ($P <0.0001$) and number of days from planting (DAP) ($P<0.0001$; Appendix 5.1ab). Full irrigation increased soil moisture, followed by PI (Fig. 5.3b). Significant interactions with soil moisture were observed between irrigation*DAP ($P<0.0001$) cultivars*DAP ($P<0.01$) and irrigation*cultivars*DAP ($P<0.01$) (Fig. 5.3ab; Appendix 5.1).



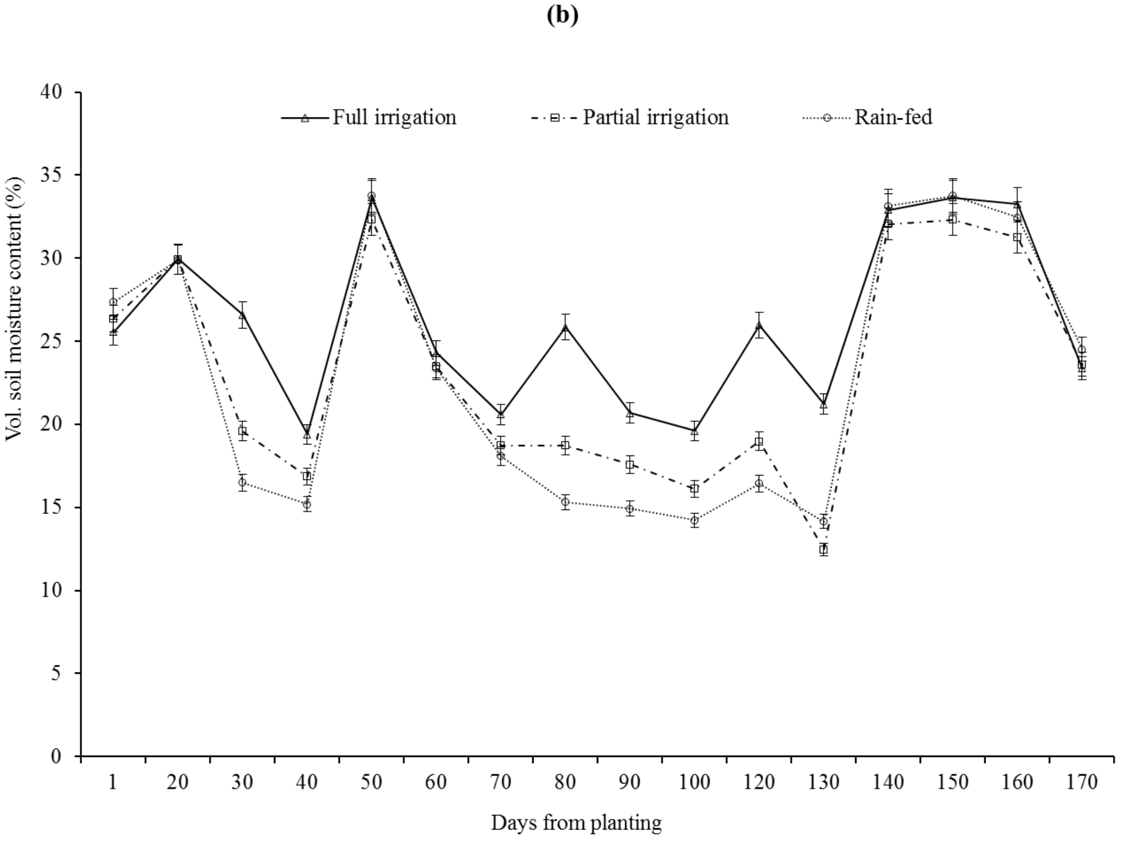


Figure 5.3 Change in volumetric soil moisture content (%) for (a) each cultivar and (b) water regime overtime.

Agria extracted more water between day 60 and 90 (Fig. 5.3a). Full irrigation increased soil moisture content, whereas N had no effect on soil moisture content ($P>0.05$). The interaction in soil moisture resulted from the differences in water inputs and cultivar water extraction differences and was highly noticed on day 80 (Fig. 5.3ab; Appendix 5.1).

5.3.2 Vegetative growth characteristics of Taewa and modern potato cultivars

5.3.2.1 Flower production and physiological maturity

Both cultivar and water regime influenced date to flowering ($P<0.0001$; $P<0.01$; Table 5.3). Tutaekuri flowered earlier than Agria and Moe Moe. Full irrigation delayed flower production. The time of flowering was not affected by N ($P>0.05$). Agria and Taewa matured 140 and 170 days after planting, respectively.

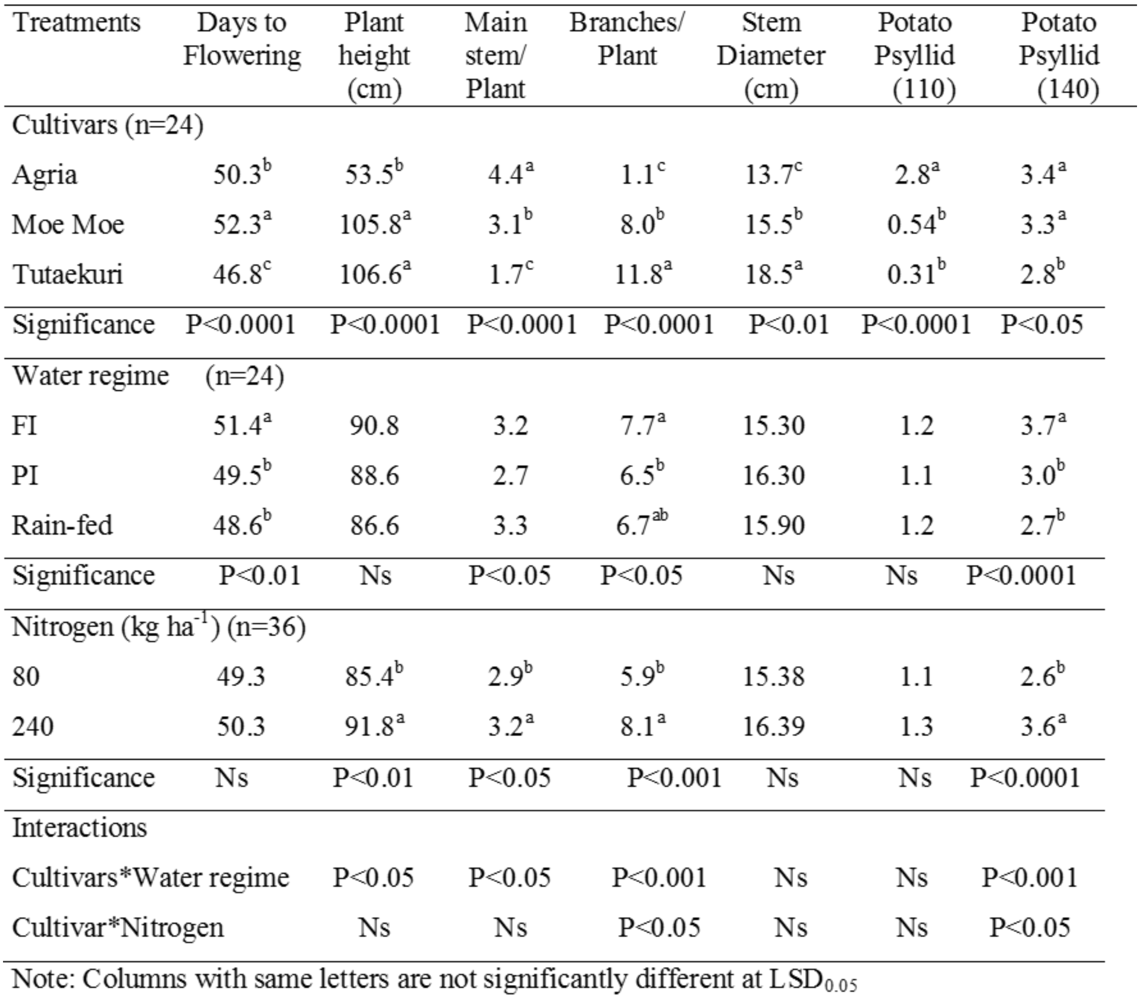
5.3.2.2 Plant height (cm)

Cultivars ($P<0.0001$) and N ($P<0.01$) influenced plant height but irrigation did not affect plant height ($P>0.05$; Table 5.3). Taewa cultivars were the tallest cultivars. The modern cultivar, Agria was the shortest. An increase in N greatly increased potato plant height by 7.5% ($P<0.01$). There were cultivar*irrigation interactions observed on plant height ($P<0.05$). This interaction involved a decrease in plant height with PI in Moe Moe, whereas Tutaekuri increased plant height with PI (Appendix 5.2a).

5.3.2.3 Number of main stems and secondary branches per plant

Potato cultivars, irrigation and N regimes influenced the number of stems ($P<0.0001$, $P<0.05$, $P<0.05$) and branches per plant ($P<0.001$, $P<0.05$, $P<0.001$) (Table 5.3). Agria had more main stems with fewer branches per plant than Taewa. However, the number of branches per plant in Tutaekuri was more than ten times those in Agria (Table 5.3). There were interactions between potato cultivars and the water regime on the number of stems per plant ($P<0.05$) and the number of branches per plant ($P<0.001$): and also between the water regime and N on the number of branches per plant ($P<0.05$). These interactions were caused by an increase in stems and branches per plant in Agria and Tutaekuri, respectively, after rainfall. High N also increased stems per plant in Taewa with the greatest increase being observed in Tutaekuri, whereas Agria had a constant number of stems (Appendix 5.2b-d).

Table 5. 3 Vegetative growth characteristics and potato psyllid scores at 110DAE and 140DAE in three potato cultivars under different water nitrogen regimes in the field, 2010/2011



Treatments	Days to Flowering	Plant height (cm)	Main stem/ Plant	Branches/ Plant	Stem Diameter (cm)	Potato Psyllid (110)	Potato Psyllid (140)
Cultivars (n=24)							
Agria	50.3^{b}	53.5^{b}	4.4^{a}	1.1^{c}	13.7^{c}	2.8^{a}	3.4^{a}
Moe Moe	52.3^{a}	105.8^{a}	3.1^{b}	8.0^{b}	15.5^{b}	0.54^{b}	3.3^{a}
Tutaekuri	46.8^{c}	106.6^{a}	1.7^{c}	11.8^{a}	18.5^{a}	0.31^{b}	2.8^{b}
Significance	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.01$	$P<0.0001$	$P<0.05$
Water regime (n=24)							
FI	51.4^{a}	90.8	3.2	7.7^{a}	15.30	1.2	3.7^{a}
PI	49.5^{b}	88.6	2.7	6.5^{b}	16.30	1.1	3.0^{b}
Rain-fed	48.6^{b}	86.6	3.3	6.7^{ab}	15.90	1.2	2.7^{b}
Significance	$P<0.01$	Ns	$P<0.05$	$P<0.05$	Ns	Ns	$P<0.0001$
Nitrogen (kg ha^{-1}) (n=36)							
80	49.3	85.4^{b}	2.9^{b}	5.9^{b}	15.38	1.1	2.6^{b}
240	50.3	91.8^{a}	3.2^{a}	8.1^{a}	16.39	1.3	3.6^{a}
Significance	Ns	$P<0.01$	$P<0.05$	$P<0.001$	Ns	Ns	$P<0.0001$
Interactions							
Cultivars*Water regime		$P<0.05$	$P<0.05$	$P<0.001$	Ns	Ns	$P<0.001$
Cultivar*Nitrogen		Ns	Ns	$P<0.05$	Ns	Ns	$P<0.05$

Note: Columns with same letters are not significantly different at $LSD_{0.05}$

6.3.1.4 Stem diameter (mm)

Water regime and N did not influence stem diameter but the cultivars showed different diameters ($P<0.01$; Table 5.3). Tutaekuri had the largest stem diameters. Agria stem diameter was the smallest and Moe Moe was intermediate. Usually, Taewa had wider stems than modern cultivar, Agria (Table 5.3).

6.3.1.5 Potato psyllid [4] infestation

Potato psyllid infestation was visually scored in late February and late March, 2011 (Table 5.3). At 110 DAE there were significant differences between potato cultivars for potato psyllid infestation ($P<0.0001$), but not between irrigation and N treatments

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[4] Potato psyllid is a vector of the bacterium "*Candidatus* Liberibacter solanacearum" which causes the disease zebra chip and other problems in potatoes (Plate 5.3), tomatoes and tomaliros.

(P>0.05). Agria was highly infested by potato psyllid by February, whilst Taewa had shown some resistance by that time. At 140 DAE psyllid scores were influenced by irrigation, N and cultivar (P<0.05, P<0.0001, P<0.0001, respectively). Full irrigation and N enhanced potato psyllid infestation, lowest score was observed in Tutaekuri. There were interactions between cultivar*irrigation and cultivar *N regimes (Table 5.3; Appendix 5.3). Simple correlation of potato psyllid, with total tuber yield with all data combined, found that potato psyllid were strongly negatively correlated with total tuber yield (P<0.0001, r = - 0.57). Potato psyllid infestation was high in FI for all cultivars and low under rain-fed in Taewa, whilst Agria had high average potato psyllid infestation. Nitrogen increased potato psyllid potentially through increased leaf area and this increase was very high in Agria, compared to Taewa (Appendix 5.3). Plate 5.2 displays the symptoms of potato psyllid infestation appeared in each of the three potato cultivars.

Plate 5.3 : Potato pysllid symptoms in Agria, Moe Moe and Tutaekuri, 2011

5.3.3 Photosynthetic water use efficiency and gaseous exchange

Cultivar significantly influenced photosynthetic WUE, A_n, g_s and Ci (P<0.01, P<0.05, P<0.05, P<0.01), but not T (P>0.05, Table 5.4). Taewa had the highest photosynthetic

WUE, A_n, g_s and lowest Ci, especially Moe Moe. Irrigation significantly affected A_n, $g_{s,}$ T and Ci ($P<0.05$, $P<0.01$, $P<0.05$, $P<0.05$), but not photosynthetic WUE ($P>0.05$) whereas, N significantly influenced A_n and g_s only ($P<0.05$, $P<0.01$).

Increased irrigation and N increased A_n, and g_s, whilst decreasing Ci, except for N. Rain-fed treatments had restricted g_s and T, resulting in low A_n. However, Ci increased with PI treatment. The high Ci in PI was accompanied by high $g_{s.}$, whilst low Ci in rain-fed treatment was accompanied by the lowest g_s. Similarly, high Ci in Agria was accompanied by low g_s. The highest Ci was in Agria with partially irrigated treatments ($P<0.01$, $P<0.5$). Nitrogen influenced A_n and g_s ($P<0.05$), but did not affect Ci, photosynthetic WUE and T ($P>0.05$; Table 5.4).

Table 5.4 Photosynthetic WUE, net photosynthesis (A_n), stomatal conductance (g_s) transpiration (T), and internal carbon concentration (C*i*) in Taewa and modern potato cultivars under different water and N regimes at 90DAE

Treatments	Photosynthetic WUE ($\mu molCO_2/m molH_2O$)	Net Photosynthesis ($\mu mol\ CO_2\ m^2\ s^{-1}$)	Stomatal Conductance ($mmol\ CO_2\ m^2 s^{-1}$)	Transpiration ($mmolH_2O\ m^2 s^{-1}$)	Internal Carbon Conc. (ppm)
Cultivars (n=24)					
Agria	2.8^{b}	6.8^{b}	71.0^{b}	2.8	223.5^{a}
Moe Moe	4.6^{a}	12.5^{a}	113.3^{a}	2.7	158.4^{b}
Tutaekuri	4.3^{a}	10.8^{a}	97.8^{ab}	2.6	166.6^{b}
Significance	$P<0.01$	$P<0.05$	$P<0.05$	Ns	$P<0.01$
Water regimes (n=24)					
FI	4.3	12.6^{a}	109.3^{a}	2.9^{ba}	166.8^{b}
PI	3.1	10.9^{a}	115.4^{a}	3.5^{a}	205.5^{a}
Rain-fed	3.9	6.7^{b}	57.2^{b}	1.7^{b}	176.8^{b}
Significance	Ns	$P<0.05$	$P<0.01$	$P<0.05$	$P<0.05$
Nitrogen ($kgha^{-1}$) (n=36)					
80	3.9	8.0^{b}	72.0^{b}	2.0	185.9
240	3.6	12.1^{a}	116.0^{a}	3.4	179.8
Significance	Ns	$P<0.05$	$P<0.01$	Ns	Ns

Note: Column rows FI and PI refer to full irrigation and partial irrigation respectively

5.3.4 Leaf water potential (Ψ_w)

Leaf water potential (Ψ_w) was significantly influenced by water regime ($P<0.0001$) and cultivar ($P<0.05$, Table 5.5). The rain-fed treatment had the lowest leaf water potential, compared to fully and partially irrigated treatment. Agria had the smallest leaf water potential amongst the three cultivars, lower than Tutaekuri, but not different from Moe Moe. Nitrogen levels did not affect the leaf water potential (Table 5.5).

Table 5.5 Effect of water and N regimes on leaf water potential (bars) in Taewa and modern potato cultivars, 2010/ 2011

Water regimes/	Potato cultivars						
	Agria		Moemoe		Tutaekuri		Mean (n=24)
Nitrogen (kg ha^{-1})	80	240	80	240	80	240	
Full irrigation	-7.4	-6.3	-7.7	-6.9	-7.9	-6.8	-7.2^{b}
Partial irrigation	-8.4	-10.1	-7.6	-7.9	-7.3	-7.8	-8.2^{b}
Rain-fed	-10.8	-11.0	-10.1	-10.3	-8.7	-8.5	-9.9^{a}
Mean (n=24)	-9.0^{a}		-8.4^{ab}		-7.8^{b}		
Significance							
Cultivars							$P<0.05$
Water regimes							$P<0.0001$
Nitrogen							Ns
$LSD_{0.05}$							1.0809

Note: Columns and rows with same letters are not significantly different at 5% LSD

5.3.5 Dry matter production and partitioning

The total dry matter production per plant was not significantly different between cultivars, irrigation and N ($P>0.05$, Table 5.6). However, partitioning of assimilates into leaves, stems, roots and tubers statistically differed between cultivars ($P<0.0001$). The water regime significantly enhanced tuber dry matter production ($P<0.0001$), whilst N significantly increased leaf and stem dry matter production per plant ($P<0.05$). Full irrigation almost doubled tuber dry matter production per plant (Table 5.6). Increased N reduced tuber dry matter production per plant in Taewa, whilst increasing it in Agria (Table 5.6).

Taewa had more leaves, stems and roots, whilst the modern cultivars had more tuber biomass per plant. Tutaekuri allocated 30% to leaves, >36% to stems and >8% to roots compared to Agria, which translocated >60% to tubers and the least to leaves, stems and roots ($P<0.0001$), whilst Moe Moe was intermediate. Generally, Agria significantly partitioned a small portion to shoots and roots compared to Taewa.

The HI after 120 DAP differed with cultivars, water and N regime ($P<0.0001$, $P<0.001$, $P<0.01$, Table 5.6. The highest HI for Agria reflected its ability to allocate dry matter to the tubers. Taewa had a significant amount of roots and root:shoot ratio compared to the modern cultivar ($P<0.05$) (Table 5.6). There were significant interactions between cultivar*N and cultivar*water regime on HI ($P<0.05$, Fig. 5.4). The decrease of HI with rain-fed treatments and the HI increase with irrigation caused the interaction between water regime and cultivars on HI. The interaction between N and cultivar was caused by a decrease in HI with N increase in Taewa, whilst it increased in Agria. (Fig. 5.4)

Table 5.6 Effect of water and nitrogen regimes on leaf, stem, root, tuber and total biomass on fresh and dry matter basis per plant (g) in three potato cultivars, 2010/2011

Treatments	Leaves (g)		Stem (g)		Roots (g)		Tubers (g)		Total Biomass (g)		Root: Shoot ratio (%)	HI (%)
	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.	Fresh Wt.	Dry Wt.		
Cultivars												
Agria	494.9	80.9^{b}	476.7	70.2^{b}	54.7	8.9^{b}	1482.0	291.1^{a}	2508.3	451.2	5.9^{c}	59.0
Moe Moe	835.7	121.8^{a}	1148.3	157.2^{a}	142.0	21.8^{a}	803.7	156.9^{b}	2929.7	457.7	7.8^{b}	28.8
Tutaekuri	864.0	117.5^{a}	1258.7	153.4^{a}	151.7	22.9^{a}	519.0	113.8^{c}	2793.5	407.6	8.5^{a}	19.0
Significance	P<0.0001	P<0.01	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	Ns	Ns	P<0.05	P<0.0001
Water regime												
FI	695.2	97.7	1026.6	129.2	112.3	16.9	1173.8	232.1^{a}	3007.8	475.8	7.4	40.1
PI	762.7	114.3	891.1	121.6	118.7	18.4	911.7	182.8^{b}	2684.1	437.2	7.6	36.4
Rain-fed	736.6	108.2	966.1	130.1	117.6	18.4	719.3	146.9^{c}	2539.5	403.4	7.7	30.4
Significance	Ns	Ns	Ns	Ns	Ns	Ns	P<0.0001	P<0.0001	Ns	Ns	Ns	P<0.001
Nitrogen (kg ha^{-1})												
80	634.4	95.0^{b}	800.6	114.3^{b}	114.1	18.13	961.3	196.99	2510.4	424.4	8.7^{a}	39.2
240	834.1	119.2^{a}	1131.0	140.3^{a}	118.3	17.63	907.1	176.97	2990.5	454.1	2.9^{b}	31.9
Significance	P<0.01	P<0.5	P<0.001	P<0.05	Ns	Ns	Ns	Ns	P<0.05	Ns	P<0.05	P<0.01
Interactions												
Cultivars*Water regime							P<0.01	P<0.05			-	P<0.05
Cultivar*Nitrogen							P<0.05	-			-	P<0.05

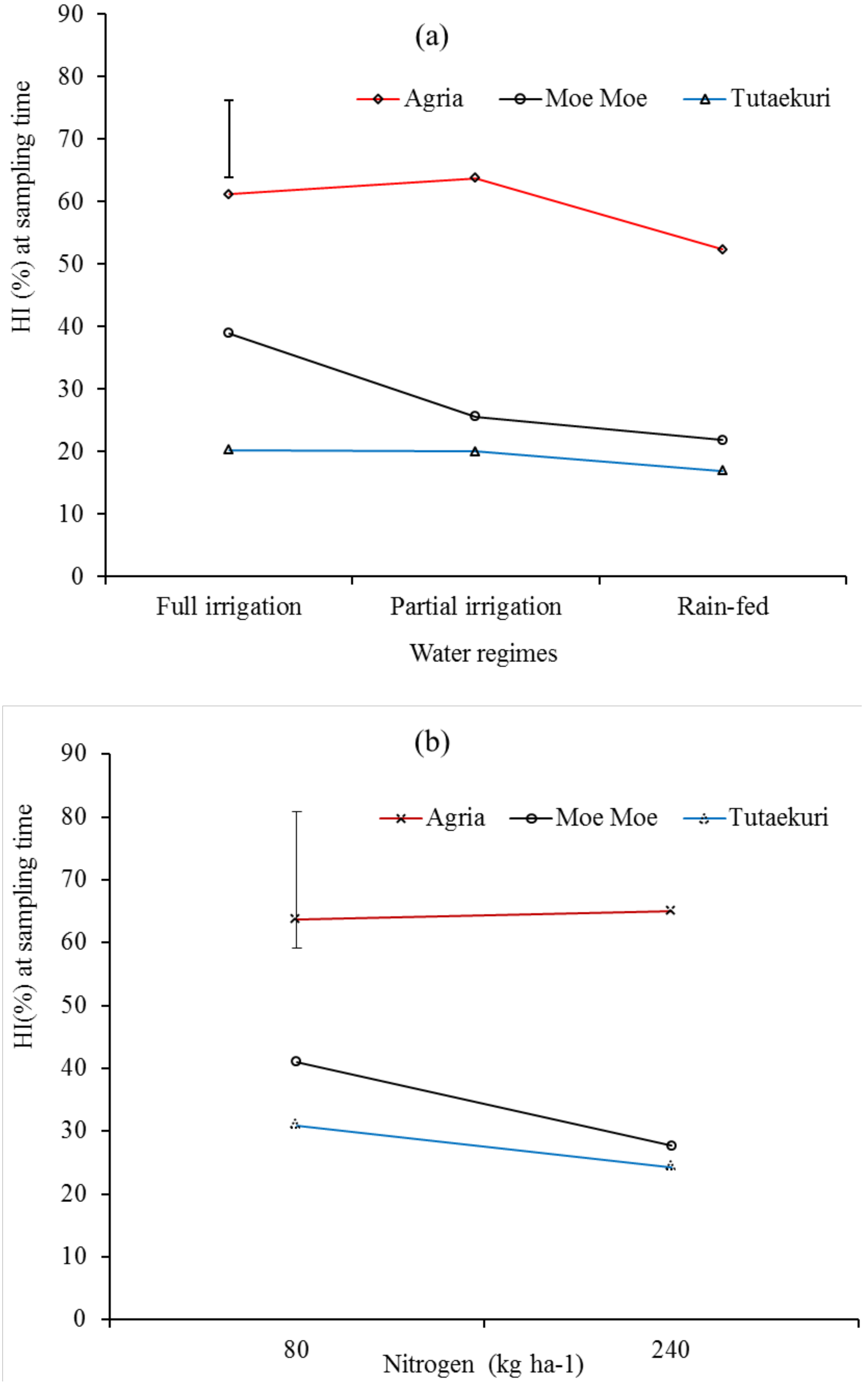


Figure 5.4 Interaction between potato cultivars and water regime (a); and interaction between potato cultivars and nitrogen (b) on HI% during biomass sampling. Error bar represents ±SEM.

5.3.6 Tuber yield and yield components

The number of tubers per plant, mean tuber weight for total and marketable tubers (g), total tuber, marketable tuber yield (t ha^{-1}) and final HI, were strongly influenced by cultivar ($P<0.0001$), irrigation ($P<0.001$) and N ($P<0.0001$, Table 5.7). Agria had the lowest number of tubers per plant. However, it had a higher mean tuber weight, HI and total and marketable tuber yield than Taewa cultivars. Tutaekuri had the highest number of tubers and lowest mean tuber weight, HI, and total and marketable tuber yield. Moe Moe was intermediate in all attributes, although the number of tubers per plant were not different to Agria ($P>0.05$, Table 5.7).

Irrigation increased the number of tubers per plant ($P<0.0001$); mean tuber weight ($P<0.05$); total tuber yield, HI ($P<0.001$) and marketable tuber yield ($P<0.0001$), but did not increase the mean marketable tuber weight (g) ($P>0.05$). Partial irrigation had a high number of tubers per plant whilst FI increased mean tuber weight; total tuber yield; and marketable tuber yield differently from PI and rain-fed. Full irrigation increased the number of tubers per plant; mean tuber weight; total tuber yield; and marketable tuber yield by 18%, 6%, 43% and 49%, whilst PI enhanced them by 24%, 6%, 26% and 13%, respectively (Table 5.7). Otherwise, high N decreased the number of tubers; total tuber yield; marketable tuber yield; and final HI by 16%, 17%, 14% and 12% respectively ($P<0.0001$). On the other hand, N did not enhance average tuber weight and final HI ($P>0.05$).

Table 5.7 Effect of irrigation and N regimes on tuber yield (t ha^{-1}) and yield components in Taewa and modern potato cultivars, 2011

Cultivars/Irrigation Nitrogen	Tubers per Plant	Average Tuber weight (g) per plant	Total Tuber Yield (t ha)	Average Marketable Tuber wt.(g) per plant	Marketable Tuber Yield (t ha^{-1})	HI (%)
Cultivars (n-=24)						
Agria	14.9^{b}	70.01^{a}	45.7^{a}	124.8^{a}	38.9^{a}	80.2^{a}
Moe Moe	15.9^{b}	39.4^{b}	27.8^{b}	66.5^{b}	22.2^{b}	48.1^{b}
Tutaekuri	28.1^{a}	16.2^{c}	20.1^{c}	29.3^{c}	14.7^{c}	47.5^{b}
Significance	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001
Water regime (n=24)						
FI	20.3^{a}	45.2^{a}	36.3^{a}	75.8	29.7^{a}	61.5^{a}
PI	21.4^{a}	41.4^{ab}	32.0^{b}	72.4	26.1^{b}	60.1^{a}
Rain-fed	17.2^{b}	39.1^{b}	25.3^{c}	72.4	20.0^{c}	54.2^{b}
Significance	P<0.0001	P<0.05	P<0.0001	Ns	P<0.0001	P<0.001
Nitrogen (kg ha-1) (n=36)						
80	21.3^{a}	47.8	34.1^{a}	74.1	27.2^{a}	62.4^{a}
240	17.9^{b}	41.0	28.3^{b}	72.9	23.3^{b}	54.8^{b}
Significance	P<0.0001	Ns	P<0.0001	Ns	P<0.0001	P<0.0001
CV (%)	16.3	20.4	11.5	17.5	14.1	10.6
Interaction						
Cultivar*Water regime	P<0.0001	Ns	P<0.0001	Ns	P<0.0001	P<0.01
Cultivar*N	P<0.01	P<0.05	P<0.0001	Ns	P<0.0001	P<0.001
Water regime*N	Ns	Ns	Ns	Ns	Ns	P<0.05
Water reg.*Cultivar*N	Ns	Ns	P<0.01	Ns	P<0.01	P<0.01

Note: WR refers to water regime, N refers to nitrogen, and column rows with same letters are not significantly different at 5% level of probability.

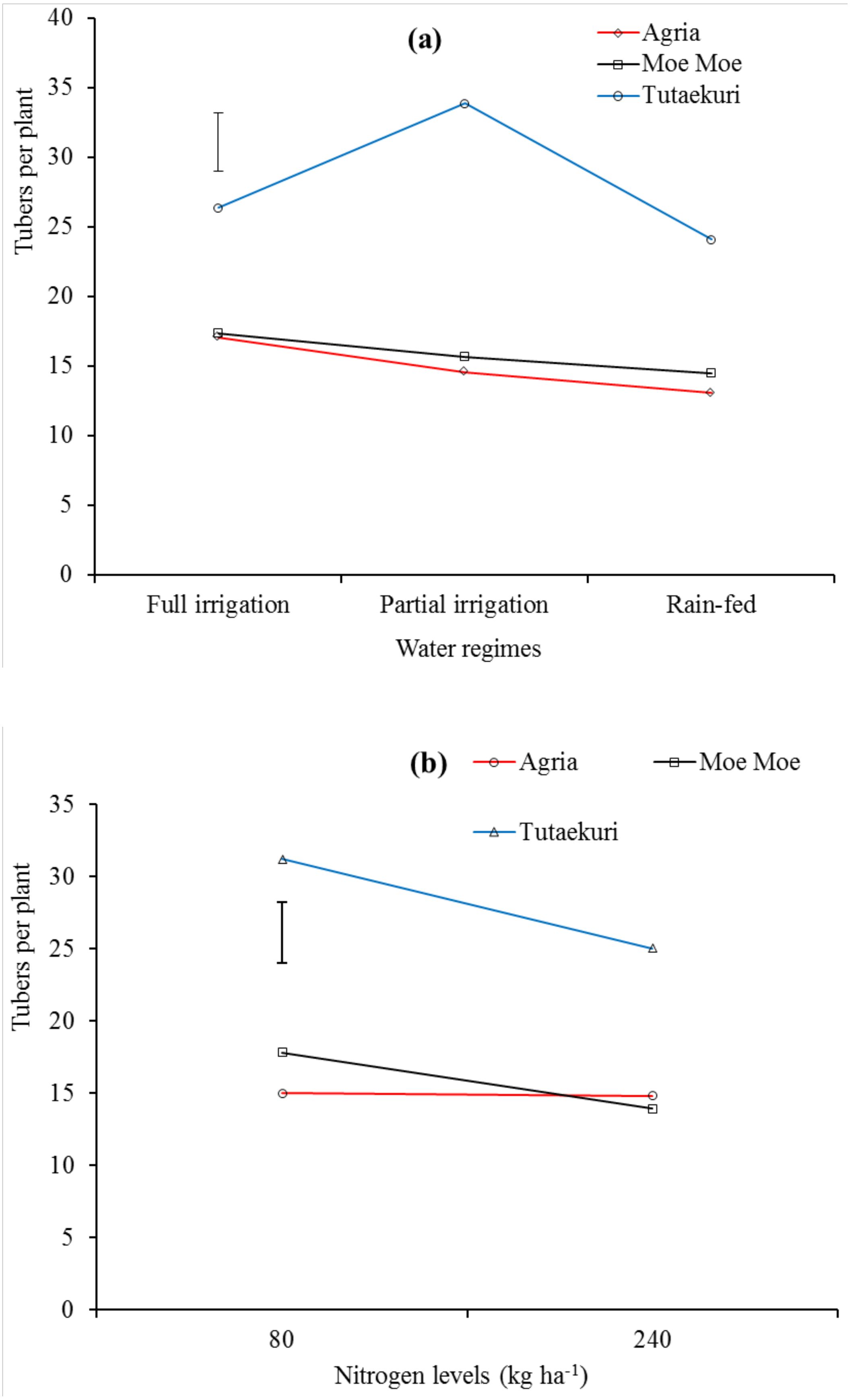


Figure 5.5 (a) Interaction between water regime*cultivar; (b) interaction between cultivar * nitrogen, on number of tubers per plant: Error bar represents ±SEM.

There were significant interactions between cultivars and irrigation on the number of tubers per plant (P<0.0001, Fig. 5.5a); total tuber yield (P<0.0001); and marketable tuber yield (P<0.0001, Fig. 5.7). Cultivar and N significantly interacted on the number of tubers per plant (P<0.01, Fig. 5.5b); mean tuber weight (P<0.05, Fig. 5.6); final HI (P<0.001); and total and marketable tuber yield (P<0.0001, Table 5.7). Significant interactions were also observed between cultivar, irrigation and N on final HI (Fig.5.9) and total and marketable tuber yield (P<0.01) (Fig. 5.8). No interactions were observed between irrigation and N (P>0.05), apart from HI (P<0.05).

The interaction involving the number of tubers per plant was a consequence of tuber decrease with FI and rain-fed, whilst it increased with PI in Tutaekuri. In other cultivars, the number of tubers decreased from FI to rain-fed (Fig.5.5a). Nitrogen reduced tuber number in Taewa but not in Agria (Fig. 5.5b). The mean tuber weight in Agria increased with N increase, whereas Taewa decreased its mean tuber weight with N increase (Fig. 5.6).

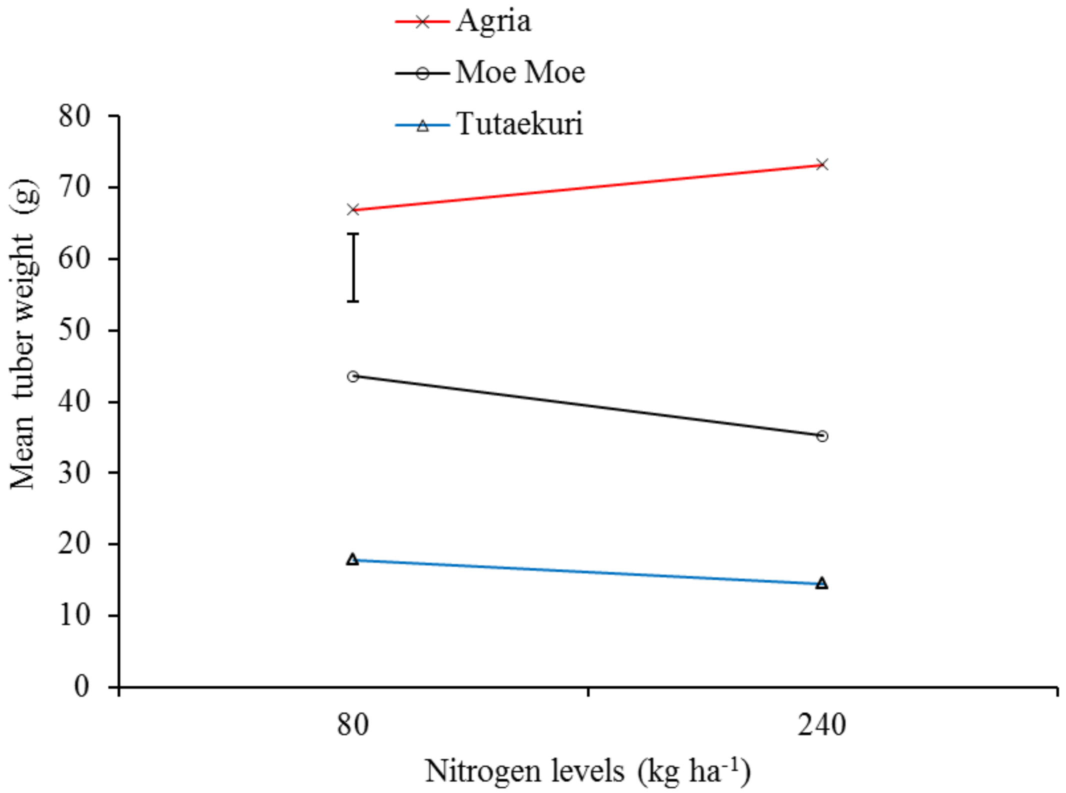


Figure 5.6 Interaction between nitrogen and potato on mean tuber weight (g). Error bar represents ±SEM.

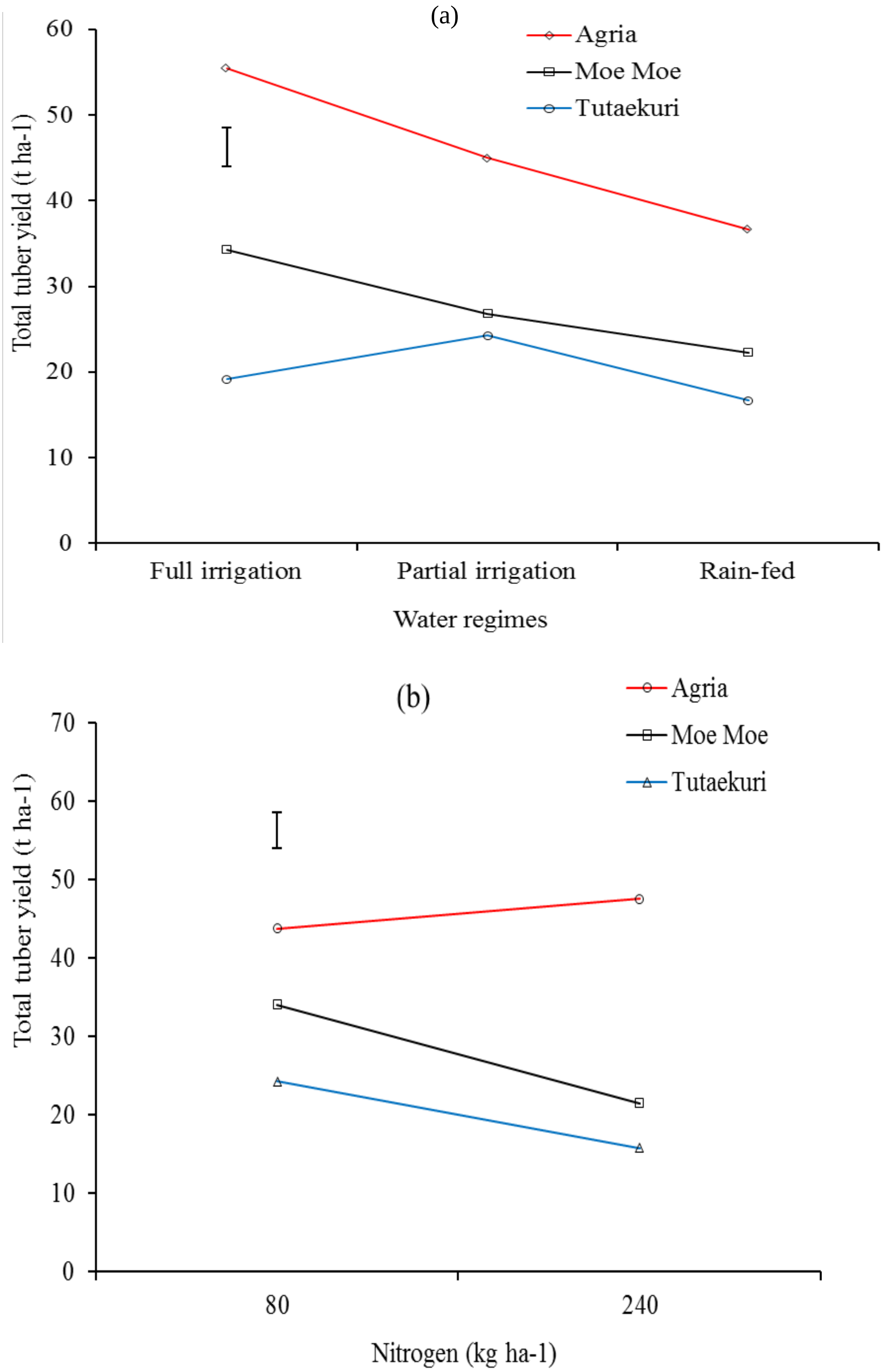


Figure 5.7 Interaction between water regime and cultivar (a), and nitrogen and potato cultivars (b) on total tuber yield. Error bar represents ±SEM.

Similarly, total and marketable tuber yield in Agria increased with high N, whilst Taewa decreased tuber yield with high N (5.7b). Water stress under rain-fed decreased the response of potato cultivars to N (Fig. 5.8). Tutaekuri performed better under PI compared to FI and rain-fed, whilst others performed well under FI (Fig.5.7a). Interaction on final HI involved an increase in final HI with high N for partially irrigated Moe Moe and Agria, whilst other irrigation scenarios reduced final HI with high N (Fig.5.9).

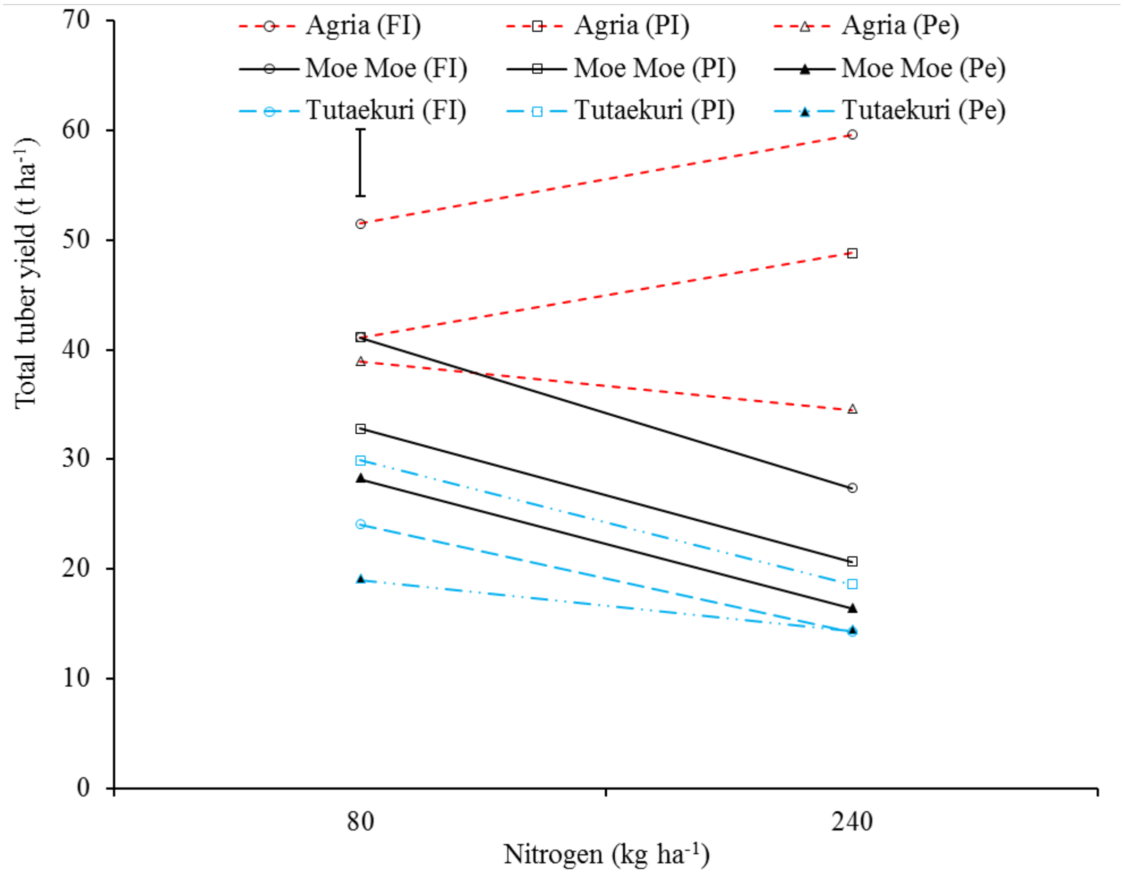


Figure 5.8 Interaction between cultivars, irrigation and nitrogen regime on total tuber yield (t ha^{-1}). Error bar represents ±SEM.

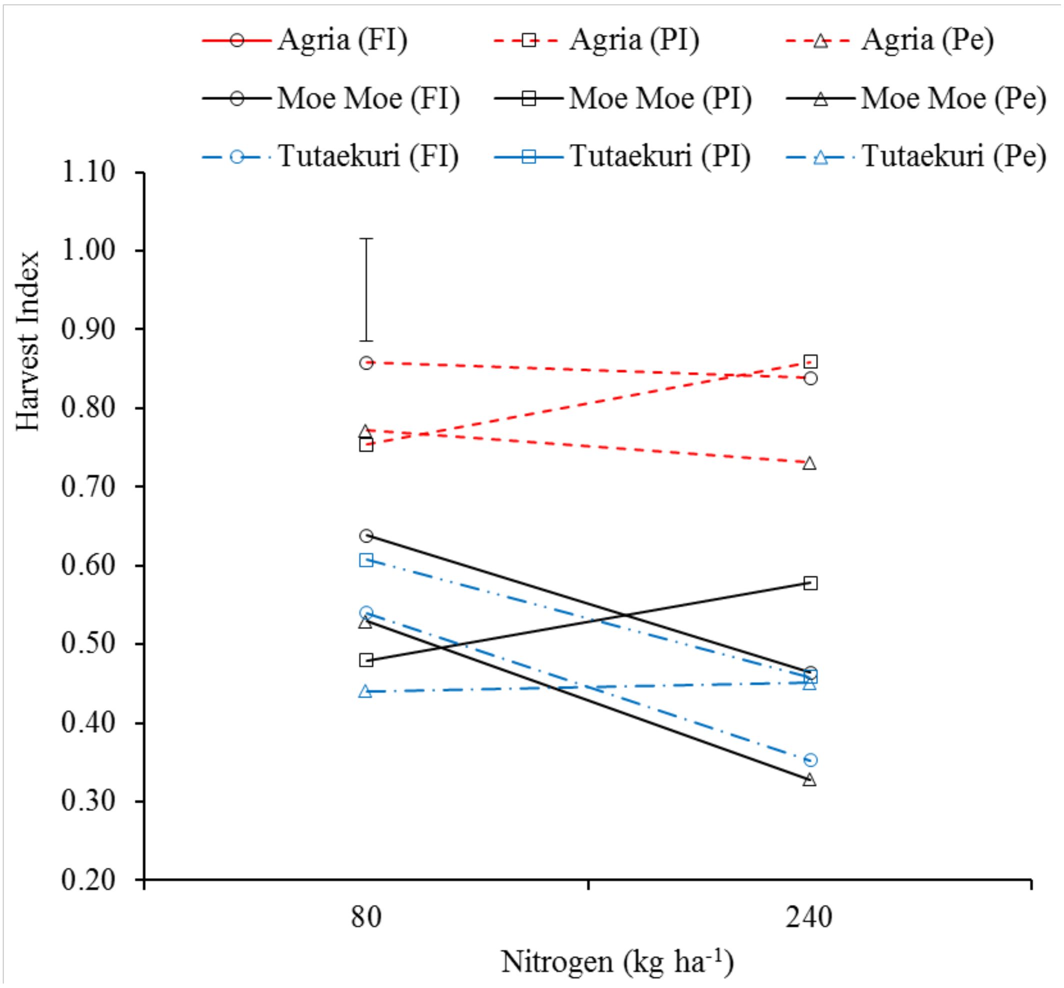


Figure 5.9 Interaction between water regime, nitrogen and potato cultivars on final HI. Error bar represents ±SEM.

5.3.7 Water use efficiency, economic water productivity and nitrogen use efficiency

Water use efficiency mirrored tuber yield, whereas economic water productivity (EWP in NZ$/m^3) reflected the product marketable value, in addition to tuber yield (Table 5.8). Water use efficiency was highest in Agria and lowest in Tutaekuri, whereas Moe Moe was intermediate (P<0.0001). Water use efficiency was significantly influenced by water regimes (P<0.001) and N (P<0.0001) in all cultivars, although differently. Water use efficiency was highest under PI and low N, whereas FI was the least in WUE. Rain-fed treatment was intermediate though not statistically different from both PI and FI (P>0.05). Full irrigation decreased WUE, whilst PI increased it in all cultivars (Fig. 5.10). Water use efficiency decreased with increasing N in Taewa and rain-fed Agria, whereas PI and FI did not reduce WUE at high N in Agria (P<0.01, Fig. 5.10).

Economic water productivity was highest in Moe Moe and lowest in Tutaekuri, whilst Agria was intermediate (P<0.0001, Table 5.8). Partial irrigation and low N increased EWP, whilst FI and high N decreased EWP ($P<0.01$, $P<0.0001$). The interaction involving EWP resulted from the increase in EWP at high N and PI in Agria, whereas Taewa had decreased EWP at high N (Fig. 5.11).

Nitrogen use efficiency was significantly high for Agria, ($P<0.0001$), FI ($P<0.0001$) and low N ($P<0.0001$; Table 5.8; Fig. 5.12). Tutaekuri, rain-fed and high N treatments had the lowest NUE. There were interaction effects between water regime*cultivars ($P<0.0001$); water regime*N ($P<0.01$); cultivars*N ($P<0.0001$); and cultivar*water regime and N on NUE ($P<0.05$) (Fig. 5.12). Full irrigation increased NUE in Agria and Moe Moe, whereas PI increased NUE in Tutaekuri. High N decreased NUE by over 300%, whereas rain-fed decreased it by 40% (Table 5.8). Partial irrigation had an intermediate influence on NUE in Moe Moe and Agria (Fig. 5.12).

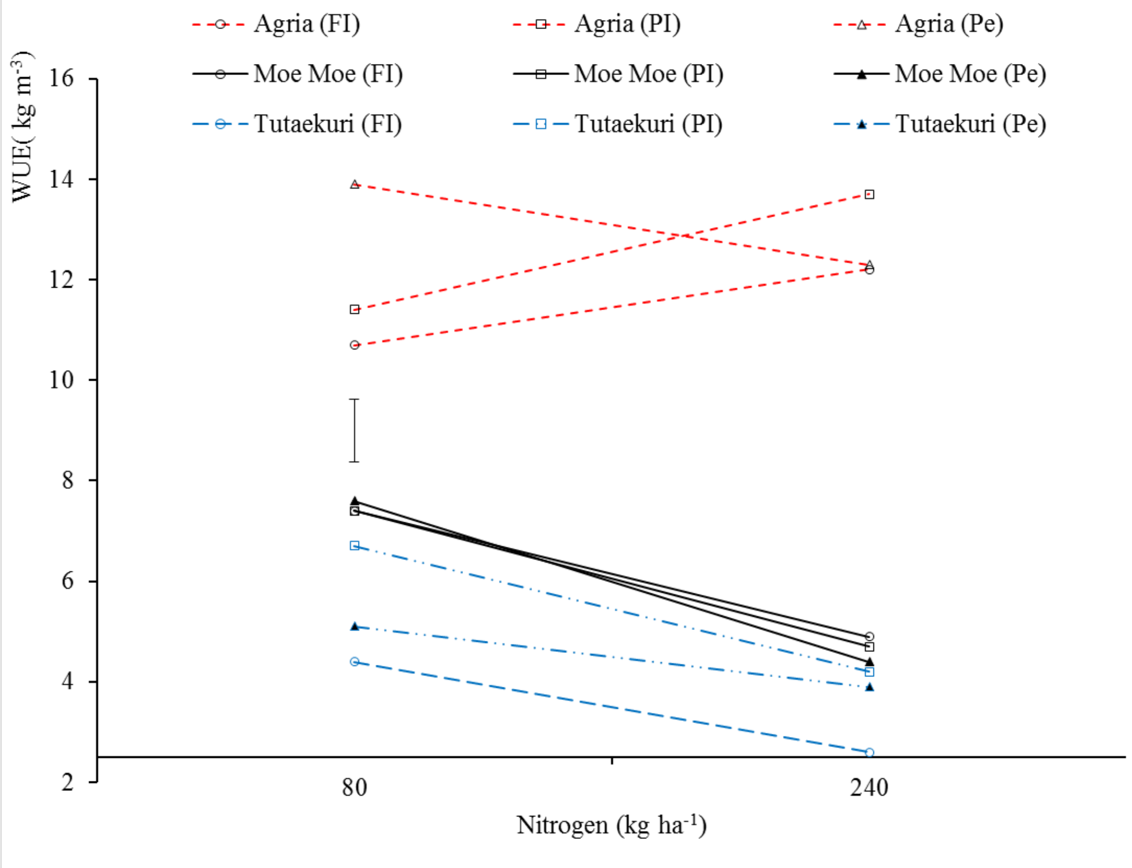


Figure 5.10 Interaction between cultivars, irrigation and nitrogen regime on WUE (kg ha^{-1} m^{3}). Error bar represents ±SEM.

Table 5.8 Water use efficiency (WUE), nitrogen use efficiency (NUE) and economic water productivity (EWP) (NZ\$/m^{3}) for Taewa and modern potato cultivars under different water and nitrogen regimes, 2010/2011

Water regime /Cultivar	WUE (kg ha^{-1} m^{3})		NUE (Kg kgN^{-1})	Economic water Productivity (NZ\$/m^{3})
	Total Yield	Market Yield		
Potato cultivars (n=24)				
Agria	12.4^{a}	10.5^{a}	373.2^{a}	14.96^{b}
Moe Moe	6.1^{b}	4.9^{b}	257.7^{b}	19.32^{a}
Tutaekuri	4.5^{c}	3.3^{c}	184.9^{c}	12.98^{c}
Significance	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$
Water regimes (n=24)				
FI	7.0^{b}	5.8^{b}	313.5^{a}	14.6^{b}
PI	8.0^{a}	6.6^{a}	277.6^{b}	17.0^{a}
Rain-fed	7.9^{a}	6.3^{ba}	224.8^{c}	15.7^{ba}
Significance	$P<0.001$	$P<0.05$	$P<0.0001$	$P<0.01$
Nitrogen (n=36)				
80	8.3^{a}	6.6^{a}	425.9^{a}	18.0^{a}
240	7.0^{b}	5.8^{b}	118.0^{b}	13.6^{b}
Significance	$P<0.0001$	$P<0.001$	$P<0.0001$	$P<0.0001$
Interactions				
Water regime*Cultivar	$P<0.01$	Ns	$P<0.0001$	$P<0.001$
Cultivar*N	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.0001$
Water regime*N	Ns	Ns	$P<0.01$	Ns
Water regime*Cult.*N	$P<0.01$	$P<0.01$	$P<0.05$	Ns

Note: Columns with same letters are not significantly different at $LSD_{0.05}$

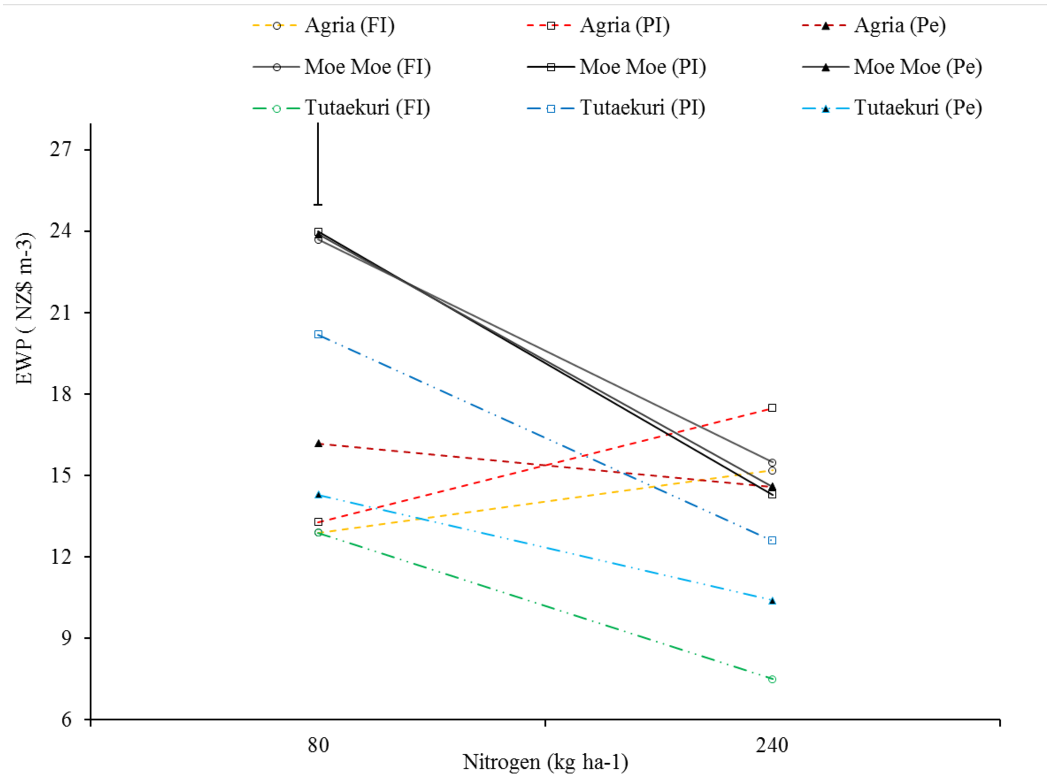


Figure 5.11 Interaction between cultivars, irrigation and N regime on EWP (NZ\$ m^{-3}). Error bar represents ±SEM.

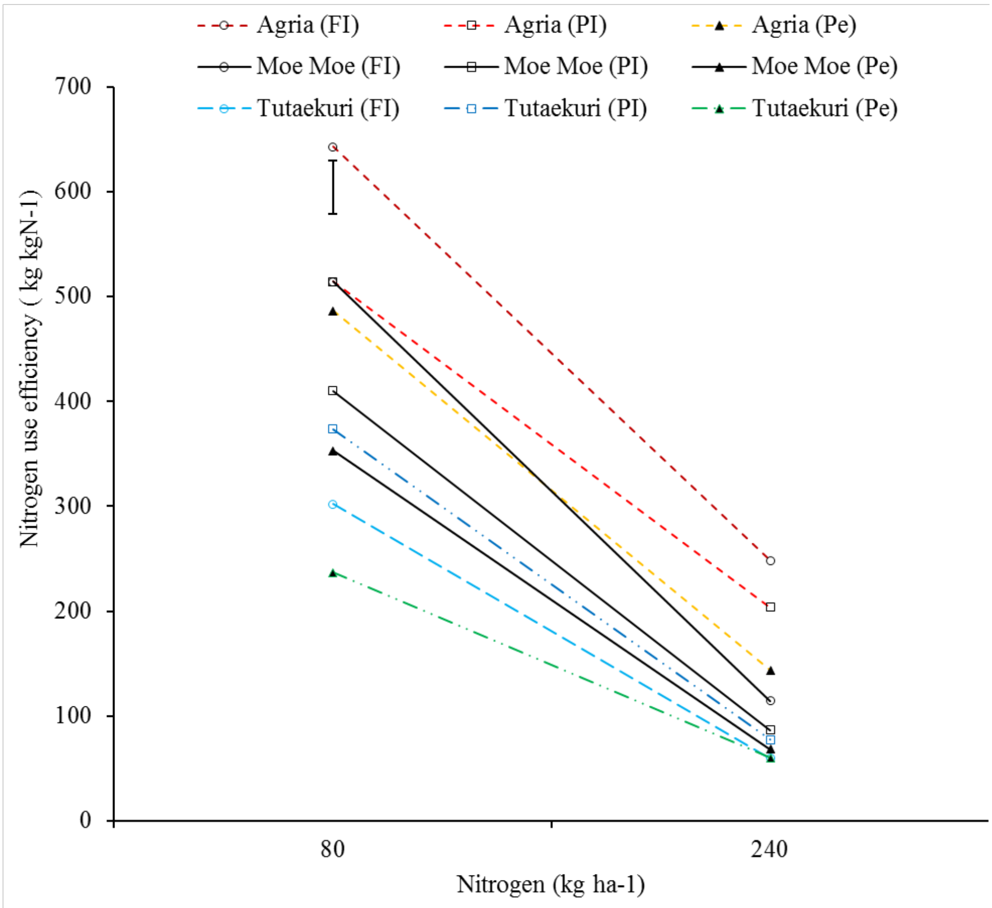


Figure 5.12 Interaction between cultivars, irrigation and N regimes on NUE (KgN kg^{-1}). Error bar represents ±SEM.

5.3. 8 Crop water production function for Taewa and modern potato

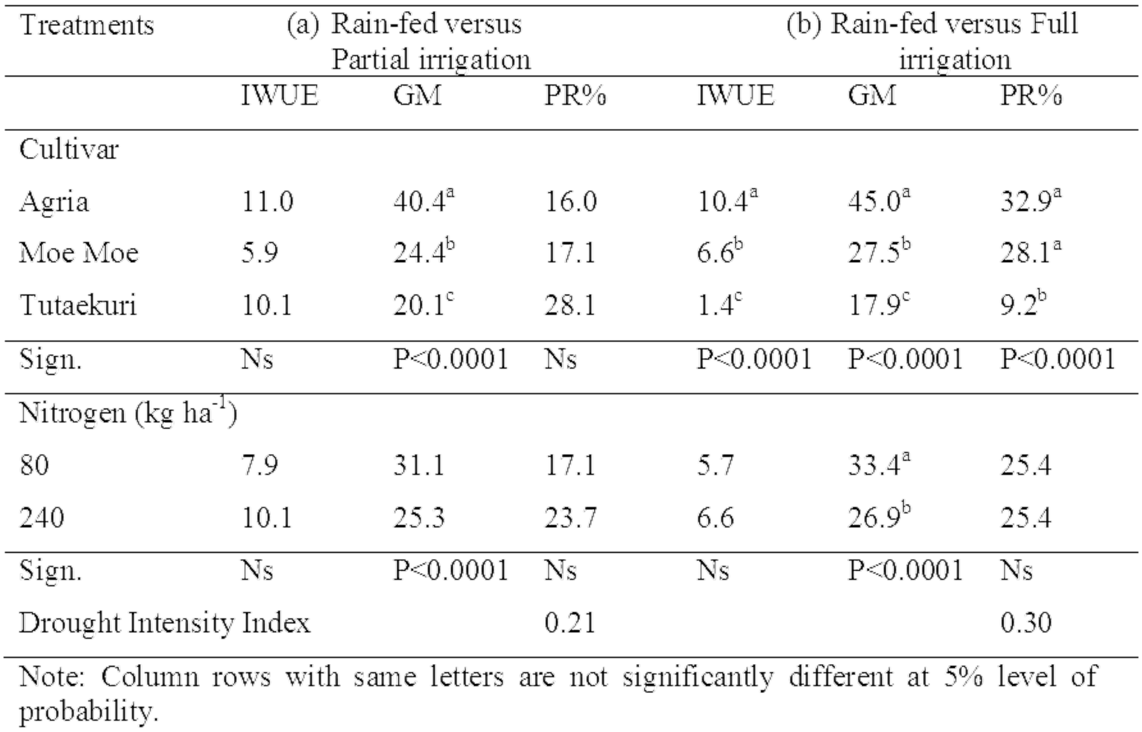
5.3.8.1 Irrigation water use efficiency (kg ha^{-1} m^{-3}) and water stress index

A regression analysis of total tuber yield and consumptive water use (CWU) with data stratified by cultivars indicated a general fresh tuber yield-water regime linear relationship (Appendix 5.4abc). Agria, Moe Moe and Tutaekuri increased tuber yield with irrigation by 8.64±1.24, 6.51±1.93 and 1.03±1.80 (kg ha^{-1} m^{-3}), respectively. The relationship significantly differed in Agria ($P<0.0001$, $r^2=0.687$) and Moe Moe ($P<0.01$, $r^2=0.34$), but it was not significant in Tutaekuri ($P>0.05$, $r^2=0.015$ (Appendix 5.4abc).

Table 5.9 presents the stratification of data by water regime, to measure change in IWUE of different cultivars, when moving from one water regime scenario to another (i.e. rain-fed to partial irrigation and rain-fed to full irrigation), in order to gather information on irrigation optimisation. Agria had the highest IWUE when both FI and PI were compared with rain-fed system; however, it was the highest under PI. Cultivar significantly differed in IWUE when FI is compared with rain-fed system ($P<0.0001$). However, N did not significantly affect yield, as production moved from rain-fed to PI or FI ($P>0.05$). Moe Moe had high IWUE when FI was compared with rain-fed scenario, whilst Tutaekuri had high IWUE when moving from rain-fed to PI and not to FI (Table 5.9).

The total yield geometrical mean and drought intensity index (DII) significantly differed under all scenarios ($P<0.0001$). The percentage of yield reduction (PR %) was significantly different under rainfed versus FI scenarios ($P<0.0001$). Geometrical mean was highest in Agria and lowest in Tutaekuri whilst PR% was highest in Moe Moe and Agria, and lowest in Tutaekuri. The water stress effect was highest when rain-fed production was opted out from FI, whereas GM was highest when FI production was opted out of rain-fed. The tuber yield reduction of rain-fed Agria, Moe Moe, and Tutaekuri were 32.9%, 28% and 9.2%, respectively, when rain-fed was opted out of FI.

Table 5.9 Comparison of irrigation water use efficiency (IWUE kg ha^{-1} m^{-3}), drought intensity index (DII), yield geometrical mean (GM) and yield % reduction (PR %) in Taewa and modern potato with different irrigation and N scenarios, 2010/2011

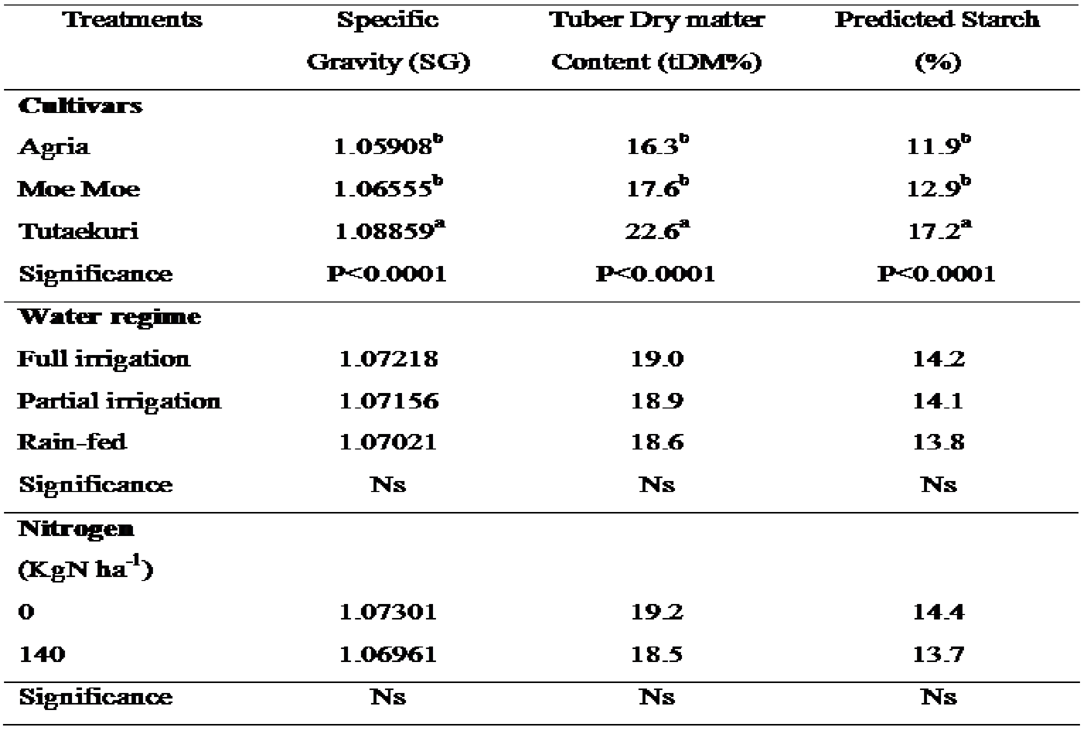


Treatments	(a) Rain-fed versus Partial irrigation			(b) Rain-fed versus Full irrigation		
	IWUE	GM	PR%	IWUE	GM	PR%
Cultivar						
Agria	11.0	40.4^{a}	16.0	10.4^{a}	45.0^{a}	32.9^{a}
Moe Moe	5.9	24.4^{b}	17.1	6.6^{b}	27.5^{b}	28.1^{a}
Tutaekuri	10.1	20.1^{c}	28.1	1.4^{c}	17.9^{c}	9.2^{b}
Sign.	Ns	P<0.0001	Ns	P<0.0001	P<0.0001	P<0.0001
Nitrogen (kg ha^{-1})						
80	7.9	31.1	17.1	5.7	33.4^{a}	25.4
240	10.1	25.3	23.7	6.6	26.9^{b}	25.4
Sign.	Ns	P<0.0001	Ns	Ns	P<0.0001	Ns
Drought Intensity Index			0.21			0.30

Note: Column rows with same letters are not significantly different at 5% level of probability.

5.3.9 Specific gravity and tuber dry matter content

Table 5. 10 Tuber dry matter (DM %) and specific gravity for Taewa and Agria, 2011



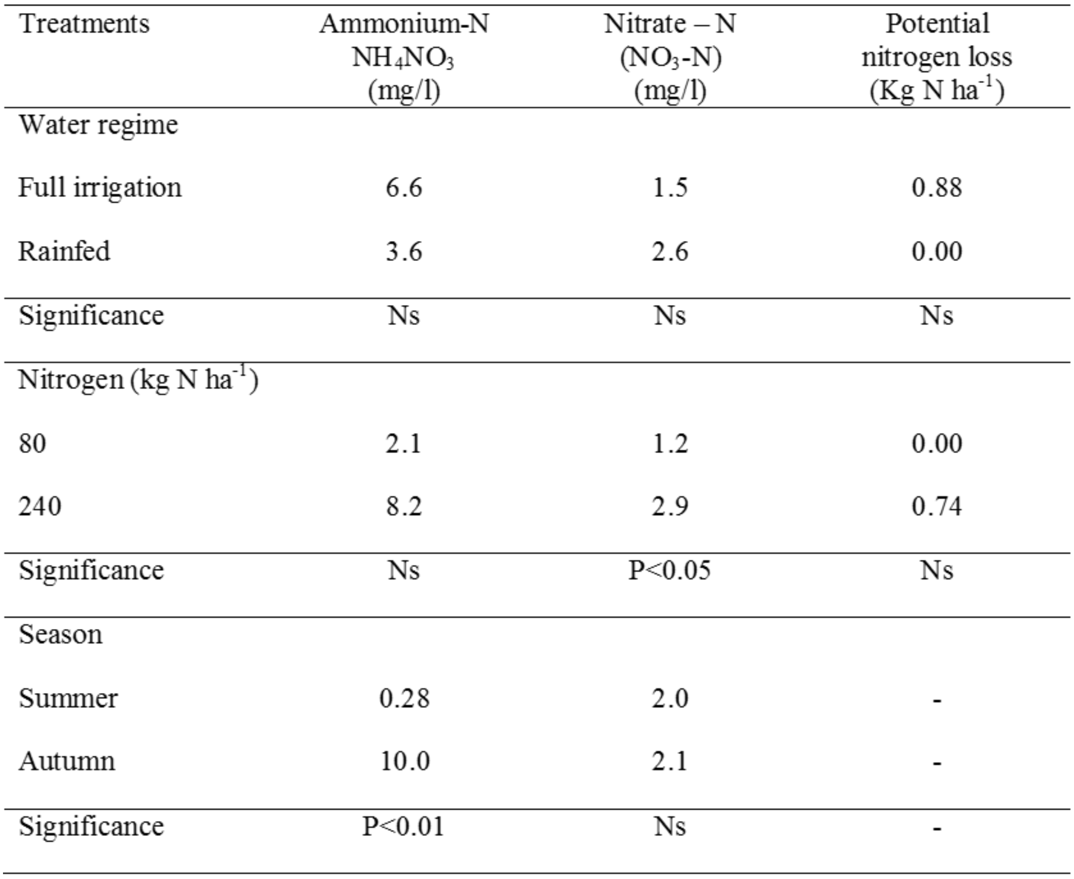
Treatments	**Specific Gravity (SG)**	**Tuber Dry matter Content (tDM%)**	**Predicted Starch (%)**
Cultivars			
Agria	**1.05908^{b}**	**16.3^{b}**	**11.9^{b}**
Moe Moe	**1.06555^{b}**	**17.6^{b}**	**12.9^{b}**
Tutaekuri	**1.08859^{a}**	**22.6^{a}**	**17.2^{a}**
Significance	**P<0.0001**	**P<0.0001**	**P<0.0001**
Water regime			
Full irrigation	**1.07218**	**19.0**	**14.2**
Partial irrigation	**1.07156**	**18.9**	**14.1**
Rain-fed	**1.07021**	**18.6**	**13.8**
Significance	**Ns**	**Ns**	**Ns**
Nitrogen (KgN ha^{-1})			
0	**1.07301**	**19.2**	**14.4**
140	**1.06961**	**18.5**	**13.7**
Significance	**Ns**	**Ns**	**Ns**

There were significant differences in SG, DM% and predicted starch between cultivars ($P<0.0001$), but not between irrigation and N regimes ($P>0.05$, Table 5.10). Tutaekuri had the highest SG, predicted starch and DM%, whilst Agria was not different from Moe Moe (Table 5.10). The results clearly indicate that the cultivar with high SG, Tutaekuri, had increased DM% and predicted starch.

5.3.10 Nitrogen concentration and potential N losses in the soil water

Nitrate-N (NO_3) concentration in soil water was influenced by the rate of N application ($P<0.05$), but it was not affected by the autumn season (Table 5.11). Ammonium-N (NH_4^+) concentration in soil water was influenced by the autumn season ($P<0.05$), but it was not affected by the rate of N application. Irrigation had no effect on both ammonium-N (NH_4^+) and nitrate-N (NO_3) concentrations in soil water. An application of 240 kg N ha^{-1} increased nitrate-N concentration in the soil water from 1.2 (mg/ℓ) at low N to 2.9 (mg/ℓ). There was a considerable ammonium concentration in soil during autumn (10.0 mg/ℓ) compared to the summer season (0.3 mg/ℓ). However, N concentrations were not significantly different between irrigated and rain-fed crops or between high N and low ($P>0.05$; Table 5.11). Potential N loss as leaching (kg N/ha) in summer and autumn were very small.

Table 5.11 Effect of irrigation on nitrogen concentration and potential N loss in the soils grown with Taewa and modern potato cultivars



Treatments	Ammonium-N NH_4NO_3 (mg/l)	Nitrate – N (NO_3-N) (mg/l)	Potential nitrogen loss (Kg N ha^{-1})
Water regime			
Full irrigation	6.6	1.5	0.88
Rainfed	3.6	2.6	0.00
Significance	Ns	Ns	Ns
Nitrogen (kg N ha^{-1})			
80	2.1	1.2	0.00
240	8.2	2.9	0.74
Significance	Ns	$P<0.05$	Ns
Season			
Summer	0.28	2.0	-
Autumn	10.0	2.1	-
Significance	$P<0.01$	Ns	-

5.4 Discussion

5.4.1 Crop water use and soil water content

The weather for Palmerston North in the summer 2010/2011 was characterised by high potential evapotranspiration and low rainfall. The volumetric soil moisture data indicate that the fully irrigated treatment maintained its water consumption closer to potential evapotranspiration, which is regarded as being crucial for the greatest yield in modern potato varieties (Ferreira *et al.,* 2007). In comparison, the rain-fed treatment failed to fully balance the water required by the plants, whereas the partially irrigated plants were maintained closer to full supply. Plant water extraction was more influenced by water availability than by genotypes.

The differences in crop water use between Taewa and the modern potato cultivars, within the irrigation schedules, were due to their life span and physiological differences (Allen *et al.*, 1998). For the rain-fed crop, Taewa used more water (360 - 550 mm) than the modern cultivar, Agria (270 - 460 mm), as observed in the previous experiment (Chapter 4). Similar results have been recorded between old and modern wheat (Siddique *et al.*, 1990a). The actual crop water use for FI (500 - 700 mm) was typical of reported values in irrigated potato (Allen *et al.,* 1998; Shock *et al.,* 2007). Likewise, Chapter 4 (Section 4.3.1) provides a potential evapotranspiration of 610 mm; this study determines 611 mm, as a benchmark for Taewa water requirement within New Zealand. However, the crop water requirement for Taewa will vary with the season and location, as reported for modern potato (Shock *et al.*, 2007), although the deviation may not be large, as observed in the 2009/2010 (Chapter 4) and 2010/2011 seasons.

5.4.2 Vegetative growth and dry matter partitioning characteristics

Taewa cultivars were tall with a few main stems comprised of multiple branches and a large number of tubers per plant (particularly, Tutaekuri), compared to the modern cultivar, Agria. Nevertheless, Taewa and Agria had equivalent total dry matter production per plant. The similarity in total dry matter was also observed in the previous field experiment (Chapter 4). This result implies that the genetic potential for total dry matter production is consistently the same between Taewa and modern cultivar. The differences between these genotypes can be found in the allocation of assimilates to harvestable tubers, with modern potato allocating >60% to harvestable tubers, whereas

Taewa allocated <60% to harvestable tubers and the remainder to shoots and roots. This confirms the observation of Geremew *et al.* (2007) that a cultivar with the highest canopy and LAI (Shepody) has a reduced tuber yield, compared to cultivars with a lower canopy and LAI. The latter were efficient in allocating more dry matter to tubers.

These findings demonstrate that old cultivars partition more dry matter to non-harvestable organs, unlike modern cultivars that partition more to the harvested organs (Ziska *et al.,* 2007). Siddique *et al.* (1990a) reported the highest HI in modern wheat cultivars and a comparable total shoot biomass between modern and old wheat cultivars. The lower root:shoot ratio observed in modern potato might have increased its HI, because modern potato cultivars have a high yield per unit root weight (Sattelmacher *et al.,* 1990), as also reported in modern wheat cultivars (Siddique *et al.,* 1990b). Sattelmacher *et al.* (1990) also confirmed that *S.andigena* has a higher root dry matter than other *Solanum species*. It is the objective of all crop breeders to increase HI as a way to increase total yield – and this has been achieved in rice, wheat, barley, maize and potato.

There is evidence that dry matter partitioning and HI also varied within the Taewa cultivars. *Solanum andigena* (i.e Tutaekuri) had the largest sink, as observed in the current and the previous studies (Kumar *et al.,* 2006). As a result, Tutaekuri had a lower harvestable component compared to Moe Moe, as illustrated by their lowest HI during sampling and final harvesting. The low HI of Tutaekuri suggests that, within Taewa cultivars, a difference in partitioning assimilates to tubers exists, as it also does between modern and heritage potato cultivars.

Full irrigation did not increase HI in Tutaekuri, compared to Moe Moe. There were large increases in HI for Agria and Moe Moe with irrigation, thus indicating how partitioning and growth characteristics vary within Taewa cultivars and other potato cultivars with irrigation (Tekalign *et al.*, 2005). However, the N increase decreased the HI of both Taewa cultivars, whilst increasing that of the modern cultivar, Agria. Nitrogen also consistently decreased HI in old cereal and potato genotypes, whilst increasing it in modern genotypes (Feil, 1992; Zebarth *et al.*, 2008). The reason for this occurrence is that N boosted the vegetative growth of Taewa, whilst reducing its NUE, which was very high in the modern cultivars (Sattelmacher *et al.,* 1990). The low partitioning of biomass to tubers in Taewa is an impediment to its adoption, otherwise the late maturity in *S.andigena* cultivar (Kumar *et al.*, 2006), such as Tutaekuri, could be advantageous in optimising solar radiation, compared to the modern cultivar, Agria.

5.4.3 Photosynthetic water use efficiency and gaseous exchange

Comparable to the glasshouse and 2009/2010 field experiments, this study found that A_n and g_s were influenced by cultivars, irrigation and N, as have other researchers (Olesinski *et al.*, 1989; Tekalign *et al.*, 2005). Taewa achieved high photosynthetic WUE and A_n by maintaining high g_s at low Ci, compared to Agria. Contrary, to the glasshouse observations, the high Ci in Agria was associated with low g_s. Agria could not steadily increase A_n even when the T was comparable to the Taewa cultivar, Moe Moe because of high Ci. This result is in line with the report on greater photosynthetic WUE being found in old wheat cultivars, rather than in modern cultivars (Koç *et al.*, 2003).

Internal carbon concentration was the main cause of variations in photosynthetic WUE and gaseous exchange between Agria and Taewa, as previously observed in the glasshouse study (Chapter 3). The relationship of Ci and photosynthetic WUE and A_n was found to be inversely linear (Figure 5.13a; Morison, 1998). Figure 5.13b confirms that A_n and g_s were curvilinearly related (Vos *et al.*, 1989a). Consequently, low g_s and high Ci reduced A_n and photosynthetic WUE in Agria. Low Ci and high g_s in Taewa enhanced their photosynthetic WUE (Fig. 5.13b). Consequently, Taewa and modern potato are different in gaseous exchange characteristics in the course of Ci and stomata conductance as observed in the glasshouse. Differences in growth stages between Taewa and the modern cultivar might prompt these variations in photosynthetic WUE at the time of the measurements. The characteristics of photosynthetic WUE for Taewa offer the potential ability for drought adaptation compared to the modern cultivar, Agria.

Water and N deficits steadily decreased g_s, as also reported by Schapendonk *et al.* (1989). Consequently, T and A_n reduced under rain-fed and low N, as reported by Olesinski *et al.* (1989). In contrast to rain-fed, partially irrigated potato achieved the higher Ci, g_s and T, which consequently increased photosynthetic capacity. On the other hand, FI moderately increased T and g_s with reduced Ci and hence the high A_n. This suggests that water stress decreased g_s whilst partial stress reduced the resistance with great T and Ci fluxes. Full irrigation stabilised g_s, Ci and T, resulting in high A_n. Consequently, photosynthetic WUE was not statically different between water regimes though FI was greater than PI, despite its high A_n. The high fluxes in Ci and T under PI reduced its photosynthetic WUE. This finding confirms that water and N deficiencies limit photosynthetic capacity (Olesinski *et al.*, 1989), whereas FI and PI improve photosynthetic capacity (Ahmadi *et al.*, 2010). However, PI failed to use water sparingly on a canopy basis, as reported under a partial root zone drying irrigation strategy (Ahmadi *et al.*, 2010), because of very high T soon after irrigation.

5.4.4 Leaf water potential (Ψ_w)

Water deficit under rain-fed conditions decreased leaf water potential, as observed in the previous field experiment. Contrary to the previous year, Taewa and modern cultivars, which were exposed to same soil moisture, significantly differed in leaf water potential, possibly due to high drought intensity compared to the 2009/2010 growing season. Taewa, particularly Tutaekuri, were very tolerant, whilst Agria was very vulnerable to water stress. This difference demonstrates genotypic variability for the management of leaf water potential between Taewa and modern cultivar. Examination of the gaseous exchange behaviour in Taewa, compared to Agria (as presented above) coupled with the leaf water potential results, supports Taewa's superior photosynthetic capacity under water stress.

Olesinski *et al.* (1989) reiterated that both leaf water potential and gaseous exchange parameters are influenced by irrigation frequency in potato. Regardless that gaseous exchange is more indicative of water stress (Olesinski *et al.*, 1989), this study shows that leaf water potential can also be used as an indicator for water stress and for irrigation guidance. Leaf water potential for FI and PI were not different in Taewa, but the two were different in Agria. The result suggests that Taewa, specifically Tutaekuri, can be scheduled at PI without more water stress, whereas Agria requires FI for the same leaf water potential with Taewa, under PI scheduling.

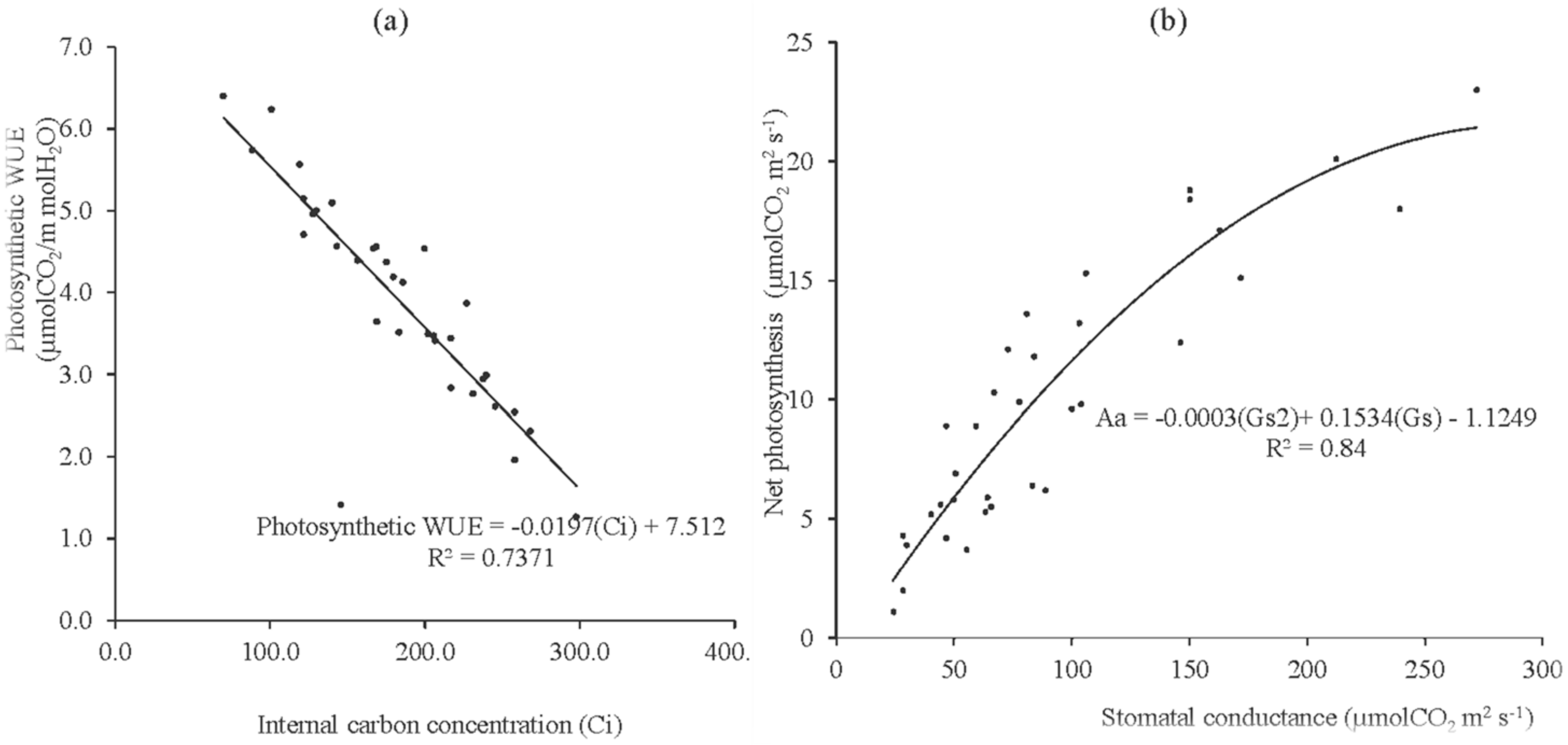


Figure 5.13 Relationship between photosynthetic WUE (PWUE) and Ci (a) and between net photosynthesis (A_n) and g_s (b) in potato cultivars

5.4.5 Tuber yield and yield components

Taewa yield response to irrigation and N was generally lower than the modern potato cultivar, Agria. For instance, Moe Moe and Agria tuber yield responded to FI, whilst Tutaekuri responded to PI. Both Tutaekuri and Moe Moe decreased total and marketable tuber yield with high N, whereas Agria increased total and marketable tuber yield with high N. The high N reduced tubers per plant, tuber weight and HI in Taewa, whilst increasing them in the modern cultivar, Agria. This indicates that, although N improves yields in irrigated potato more than in water-stressed fields (Ferreira *et al.*, 2007), the response to N depends on cultivars, as reported for Agria, Fianna, Russet Burbank, Ilam Hardy and Kennebec cultivars in New Zealand (Craighead *et al.*, 2003). Consequently, Craighead *et al.* (2003) recommended N application up to 210 - 250 kg ha^{-1} as a suitable range for tuber yield response in New Zealand. Taewa growers do not need to apply the amount of N applied to modern potato cultivars.

Irrigation enhances tuber yields through the modification of partitioning more assimilates to the tuber, depending on the cultivars (Belanger *et al.*, 2001; Walworth *et al.*, 2002). In this study, FI moderately improved the number of tubers, HI and mean tuber weight in Agria and Moe Moe, whilst decreasing them in Tutaekuri. The tuber yield improvement with irrigation and N in Tutaekuri was greatly limited by genotypic potential. Consequently, the large tuber numbers per plant and small tuber size hampered Tutaekuri tuber yield. This supports documentation which describes *S.andigena* yields as primitive and limited by large above-ground biomass (Kumar *et al.*, 2006). Nevertheless, the current study indicates the possibility of achieving higher tuber yields in Tutaekuri, with PI and low N. This study has also confirmed the previous failure of FI to improve Tutaekuri tuber yield, in a glasshouse (Chapter 3) and in the field (Chapter 4).

In this study, Agria demonstrated high yield potential compared to the Taewa cultivars. Moe Moe did not compete well with Agria, compared to the glasshouse and 2010 field experiments. The relative low yields of Moe Moe in this study are most likely to have been the result of potato psyllid infestation (*Bactericera cockerelli*), during the late stages of the crop. Visual surveillance showed potato psyllid symptoms 110 - 150 days after planting (Fig. 7.1). The attack had less impact on Agria yield, since it had already developed tubers, whilst Taewa was still developing tubers when infested: hence, Taewa yields were probably decreased due to the pest's disruption of the photosynthesis and tuber dry matter accumulation process. On the other hand, the performance of irrigated Moe Moe still contradicts statements that Taewa cultivars are 50% poorer in their tuber yields, compared to modern cultivars (Harris *et al.,* 1999).

This study is illustrative of the claim that the low tuber yields commonly reported for Taewa may be at least partly due to pests and diseases and soil water management. However, these tuber yields are considerably above the current mean total and marketable tuber yields attained by Taewa growers, ranging from 15 - 20 t ha^{-1} and 10 - 15 t ha^{-1}, respectively (Roskruge, 2011 pers. comm.). Irrigation contributed to improvement in the tuber yield of Taewa, although this was restrained by potato psyllid. Full irrigation and PI, respectively, raised Moe Moe and Tutaekuri tuber yields towards a potential yield of 40 t ha^{-1}.

5.4.6 Water use efficiency, economic water productivity and nitrogen use efficiency

The average WUE varied with cultivar, irrigation and N regimes, ranging from 4.5 kg m^{-3} (Tutaekuri) to 12.4 kg m^{-3} (Agria) amongst cultivars; 7.0 kg m^{-3} (FI) to 8.0 (PI) amongst irrigation; and 7.0 kg m^{-3} (high N) to 8.3 kg m^{-3} (low N) amongst N regimes, respectively. The WUE amongst cultivars compares to 8 ℓ/100g, 16.4 ℓ/100g and 22 ℓ/100g virtual water content for Agria, Moe Moe and Tutaekuri, respectively. This is lower than the estimate of mean global virtual water content of 25 ℓ/100 g potato tuber (Hoekstra *et al.,* 2007).

Agria was more efficient in water use than the mean global WUE of 6.2 - 11.6 kg m^{-3} (FAO, 2009), whilst Moe Moe, under low N, was within this range. Tutaekuri was less than 6.2 kg m^{-3}, except when partially irrigated and subjected to low N treatments. The mean WUE for Taewa is below the range reported by FAO (2008, 2009), due to the impact of potato psyllid infection and high N on tuber yield. Nevertheless, furrow and drip irrigation studies for modern potato have also reported WUE within Taewa's low range of 2.6 - 7.5 kg m^{3} (Erdem *et al.,* 2006).

Partial irrigation was a significant water saving strategy, through the lowering of actual ET below full water supply, whilst keeping a tuber yield that approached the tuber yield of FI. This helped PI to achieve high WUE and EWP without a much decline in tuber yield and quality. The EWP for the three water regimes was 11.40 US$/m^3 (FI), 13.26 US$/m^3 (PI) and 12.25 US$/m^3 ($P_e$). The EWP realised from this study are higher than 0.3 US$/m^3 reported in Jordan for potato tuber yield (FAO, 2003; Molden *et al.,* 2001). It is probable that the variations in EWP and WUE can be attributed to management, climate, market price and genotypes. This study has shown that PI had both physical and economical water saving attributes. The use of high WUE potato cultivars, high market value cultivars, moderate N and appropriate irrigation scheduling, facilitates the maximisation of crop water productivity (Wallace, 2000; Morison *et al*., 2007).

Cultivars and N consistently influenced WUE and NUE differently within the various water regimes (Battilani *et al.,* 2004; Zebarth *et al.,* 2008). In this study, WUE and NUE were highest in Agria at high N and low N, respectively. The low N that limited WUE in Agria improved WUE in Taewa. High N led to both low NUE and WUE in Taewa. Similarly, PI had high WUE in Agria at high N, whilst it had deteriorating NUE. The FI that increased NUE in Agria and Moe Moe reduced its WUE. This finding supports several studies of modern production systems that have reported an increase in NUE with adequate water, whilst decreasing WUE (and vice versa) and that WUE is high where water is limited (Battilani *et al.,* 2004). However, WUE in Taewa was influenced more by N than by irrigation scheduling. Generally, more water and N increase tuber yield of modern cultivars, whilst Taewa (especially Tutaekuri) requires lower quantities of water and N for higher productivity. This response suggests that Taewa and modern potato cultivars have different appropriate irrigation and N levels for efficient resource use. Therefore, growers should take into account the potato genotypic response to water and N for efficient water use.

5.4.7 Irrigation water use efficiency

The tuber yield - water relationship for both Taewa and modern potato was linear, as also documented in most modern potato experiments (Ferreira *et al.,* 2007). However, the tuber yield increase with irrigation was low in Taewa compared to the modern cultivar. Irrigation water use efficiency for Agria and Moe Moe was within the range (5.2 - 9.1 kg m^{-3}) reported by Ferreira *et al.* (2007), in a hot dry environment, but Agria was above IWUE for New Zealand (Hedley *et al.,* 2009b). In New Zealand, the IWUE for uniform and variable rate irrigation are 5.8 and 6.8 kg m^{-3} (Hedley *et al.*, 2009b). The IWUE for Moe Moe was within this range. Tutaekuri had lower IWUE than what has previously been reported in a temperate and hot dry environment. In contrast to Ferreira *et al.* (2007), N had no influence on IWUE. In spite of high IWUE in modern cultivars, the yield reduction with water deficit indicates that it is more vulnerable to water stress compared to Moe Moe and Tutaekuri. Moe Moe is reliable for both irrigated and rain-fed conditions, whilst Agria is only reliable under full irrigation.

5.4.8 Specific gravity and tuber dry matter content

Specific gravity and DM are more strongly influenced by cultivar (Jefferies *et al.,* 1993b) than irrigation and N (Bélanger *et al.,* 2002). Taewa cultivars are high in DM and SG compared to Agria, thus indicating great tuber quality. The SG range in Taewa (particularly Tutaekuri) was within the normal SG range of 1.055 to 1.0950 (Kellock *et al.,* 2004), unlike the previous year (see Chapter 4, Section 4.3.1) and the glasshouse results (Chapter 3), which were above these values. Nevertheless, SG and DM for Tutaekuri demonstrated Singh’s (2008) and Chapters 3 and 4 findings that SG and DM in Taewa are high compared to modern cultivars. Genetic factors and the late maturity of Taewa enhanced the accumulation of DM (Werner *et al.,* 1998). It is probable that psyllid infestation disrupted the DM accumulation process in Taewa, thus resulting in lower DM and SG than previous years as once reported in modern potato by Teulon *et al.,* (2009).

Tutaekuri had the highest predicted starch concentration followed by Moe Moe and then Agria. Specific gravity and DM are positively related to starch, but negatively related to sugar concentration (Iritani *et al.,* 1976). This means that Agria had a high concentration of total sugars, as determined in Chapter 4 (see Section 4.3.1). For instance, reduced sugars and DM are usual benchmarks for processing potato quality assessment (Marquez *et al.,* 1986). The low DM in Agria would reduce productivity of the processed product and the amount of oil used for processed products, compared to Taewa (Kellock *et al.,* 2004). This implies that Taewa can produce more processed products with less oil, compared to modern cultivar, Agria.

5.4.9 Nitrogen concentration and potential N loss in the soil water

The concentration of ammonium-N in the soil water was found to be greater than the concentration of nitrate-N but there was no difference in N loss between treatments. This study does not show that irrigation of potato necessarily results in high N leaching (Francis *et al.,* 2003; MAF, 2002). The possibility of nitrate leaching into the groundwater was not noticed in high N application or autumn season. The possible reason is that the N rate in this study is lower than 400 kg N ha^{-1} applied by most growers in New Zealand (Martin *et al.,* 2001). This result suggests that low N practices can provide an acceptable nitrate leaching measure for Taewa growers.

5.5 Conclusion

The effect of irrigation and N on vegetative growth, dry matter partitioning, photosynthetic WUE, DM and SG characteristics, N leaching, tuber yield, WUE and NUE in Taewa, were compared with the modern cultivar, Agria, in the field. Under FI, 92% of the 611 mm potential water requirement was supplied, whilst rain-fed supplied 60% and PI met 73%. Taewa used more water than Agria. Taewa grew wide bushes with tall main stems with multiple branches and large numbers of small tubers per plant, whilst the modern cultivar had a high number of short stems. The total dry matter production for Taewa and modern potatoes were the same, except that modern potato partitioned more to tubers, whereas Taewa allocated more assimilates to tubers to the shoots and roots.

Photosynthetic WUE and A_n differed with cultivars, irrigation and N, with the highest photosynthetic WUE and A_n in Taewa. Taewa achieved high photosynthetic WUE and A_n by maintaining high g_s at low Ci compared to Agria. Taewa and modern potato differed in gaseous exchange, in the course of stomata conductance and because of growth stage differences. Full irrigation and N increased photosynthetic WUE and $A_{n.}$. In addition, Taewa was very tolerant to water stress, whilst Agria was very vulnerable to water stress. This point is illustrated by the leaf water potential results. The characteristics of photosynthetic WUE and leaf water potential for Taewa offers a great physiological ability for drought adaptation, compared to the modern cultivar. It was also observed that Taewa had high DM and SG, compared to modern potato cultivars. It can be concluded that, in relation to physiological characteristics, Taewa has high vegetative growth, photosynthetic WUE, DM and SG, compared to modern potato cultivars. However, the modern cultivar was excellent in partitioning to tuber dry matter and early maturity.

Taewa tuber yield, WUE, EWP and NUE are more sensitive to high N than the modern cultivar, Agria. However, Agria is more responsive to water stress than Taewa and therefore, Taewa require a low N in combination with PI, especially Tutaekuri, whereas Moe Moe requires a low N in combination with FI. Agria requires high N in combination with FI. Moe Moe indicates that it has the potential to compete with modern cultivar, if appropriate pest and disease management is put in place. The high EWP in Moe Moe may allow growers to economically and physically optimise their water resource use.

It is suggested that Tutaekuri and Moe Moe also differ in some of their morphological and physiological characteristics. Tutaekuri has fewer stems with more branches, many small tubers and larger stems and a higher shoot: root ratio than Moe Moe. On the other hand, the tuber yield, HI, WUE, EWP and NUE for Tutaekuri are smaller than that for Moe Moe. Tutaekuri responded to PI and it had low PR%, whilst Moe Moe performed well under FI. Both Tutaekuri and Moe Moe required very low N, and, therefore, it can be concluded that genotypic variation is high within Taewa and between Taewa and modern potatoes.

CHAPTER 6

EFFECT OF MECHANICAL AND HORMONAL CANOPY MANIPULATION ON TAEWA UNDER LIMITED AND UNLIMITED WATER AND NITROGEN CONDITIONS

6.1 Introduction

Tutaekuri, also known as Urenika (*Solanum tuberosum ssp. andigena)* is a distinctive Taewa or Maori potato cultivar (Harris, 2001). It is the most widely cultivated Taewa in New Zealand. The tubers are elongated with a dark purple skin and they have a very flourly flesh which fragments when boiled. The morphology of the Tutaekuri plant also exhibits the distinguishing features of undeveloped potato cultivars: long stolons, very deep eyes and late tuberisation. Harris (2001) described Tutaekuri as one of the Taewa cultivars still exhibiting the true ancestral characteristics of the Andean potatoes.

Tutaekuri has also been characterised by a large shoot biomass, many branches, many small tubers per plant and insensitivity to full irrigation compared to modern potato cultivars (Chapters 4 and 5). Tutaekuri is also known to possess high antioxidant activity (Lister, 2001), high tuber dry matter content and specific gravity (Singh *et al.*, 2008) (Chapters 3 & 4). However, it is handicapped by small tuber size and low yields like in other *Andigena* spp (Kumar *et al.*, 2006). High above-ground biomass suggests that Tutaekuri has the potential for yield improvement, through the manipulation of its shoot biomass and number of tubers. It was hypothesised that Tutaekuri utilizes a greater proportion of assimilates for above-ground dry matter production, rather than for tubers. Subsequent reduction of the leaf canopy, either by application of growth regulatory hormones or mechanical control, would stimulate increased allocation of assimilates to tubers.

Tutaekuri appears to strongly favour the source of assimilate (shoots) over the below-ground sinks (tubers). The results of an earlier experiment show high photosynthetic capacity and LAI, accompanied with low tuber yield, in Tutaekuri (Chapters 3, 4 and 5). Consequently, above-ground dry matter production was greater than the tuber dry matter production. Gifford *et al.* (1981) indicated that plants with sinks, which strive effectively for assimilates, experience reduced vegetative growth, due to heavy tuberisation. However, it is not known whether the above-ground sink size actually control partitioning to the below-ground sink in Tutaekuri.

Physical alteration of a large leaf canopy reduces water use, whilst increasing yield in potato (Hossain *et al.*, 1992), wheat (Richards, 1983) and temperate pasture (John *et al.*, 1973). Numerous studies have also established that the application of chlorocholine chloride (CCC) enhances tuberisation in *Solanum tuberosum* (Wang *et al.*, 2010a) and *Solanum tuberosum ssp. andigena* (Kumar *et al.*, 1974). Mechanical topping and CCC reduce competition between the canopy and tubers for assimilates. Chlorocholine chloride impedes vegetative growth in potato crops by hindering gibberellin, but improving tuberisation and photosynthetic capacity (Wang *et al.*, 2010). Nevertheless, there have not been any leaf canopy modification studies on Taewa cultivars in New Zealand, in order to characterise the effects of mechanical topping and CCC spray schedules on the partitioning of photoassimilates between the source and the sink, under field conditions. This field experiment examined the consequences of mechanical canopy topping and CCC foliar application on dry matter partitioning, tuber yield and water use efficiency in the Taewa cultivar, Tutaekuri (*Solanum tuberosum ssp. andigena*), under limited and unlimited water and nitrogen environments. The purpose for this study was to improve the yield and WUE of Taewa cultivar, Tutaekuri.

6.2 Material and Methods

6.2.1 Experimental Site

The field experiment was conducted at the Pasture and Crop Research Unit, Massey University, Palmerston North, New Zealand. It was planted on 27th October 2010 and harvested on 15th April, 2011. The soil and weather for site have been presented in Table 5.1 and Figure 5.2 (See Chapter 5).

6.2.2 Experimental design and crop management

6.2.2.1 Treatments and experimental design

The field experiment was a Randomised Complete Block Split-Split-plot Design (RCBD Split-Split-plot) with two water regimes as the main treatments (rain-fed and full irrigation); four canopy manipulations as sub-treatments; and two fertiliser rates (N1=0 and N2=140 kg ha^{-1}) as sub-sub-treatments. This was replicated four times (Fig. 6.1). Both fertiliser treatments received PK as a basal dressing and N was applied as a side dressing of urea.

6.2.2.2 Leaf canopy manipulation treatments

The four canopy manipulation treatments were as follows: (1) normal growth as a control (NGC); (2) application of CCC (2-chloroethyltrimethyl-ammonium chloride, at 2 g l^{-1} (2000 ppm), twice during the tuber initiation stage at 25 and 30 days after plant emergence (DAE), coded as 25-30 CCC (Wang *et al.*, 2009a); (3) application of CCC at 2 g l^{-1} (2000 ppm) twice during the tuber initiation stage at 25 and 50 DAE, coded as 25-50 CCC; and (4) mechanical canopy topping. Mechanical canopy topping was implemented by cutting the shoots on top of the potato bush by one third of the plant (Plate 6.1).

A manual hedge shear with heavy duty precision cutting blades was used for topping the canopy 52 DAE on 7th January, 2011. Chlorocholine chloride was applied (from cycocel 750 brand manufactured by OHP, INC.) using a backpack sprayer at 350 litres of water per hectare. Both CCC treatments received an initial treatment on 12th December, 2010. The second application for the 25-30 CCC treatment was applied on 17th December, 2010. The second application for the 25-50 CCC treatment was applied on 3rd January, 2011.

6.2.2.3 Irrigation and fertiliser application

The irrigation treatment received 25 mm irrigation at 30 mm soil moisture deficit (SMD), between 4th December, 2010 and 20th March, 2011. Irrigation was applied by Trail boom traveller irrigator. Crop water use, for irrigated and rain-fed treatments, was determined by the soil water balance approach (see Chapter 4). All plots received 30 kg P and 75 kg K ha^{-1} (at planting) of Potash Super 30% fertiliser (0-6-15-8) applied at 500 kg ha^{-1}. The crop on NPK fertiliser treatment received 140 kg N ha^{-1} from urea (as a side dressing), whilst the other crop did not have applied. Nitrogen fertiliser was applied on 10th December, 2010, 24 DAE. This was followed by mounding on the same day. All other field husbandry practices (i.e. weeding and plant protection) were carried out, as previously described in Chapter 5.

6.2.3 Plot-size and plant spacing

Potato tubers were manually planted on 27th October, 2010, at 75 cm spacing between rows and 30 cm spacing within rows, at a depth of 10 - 15 cm. Each plot was 3 m by 1.5 m, containing 18 plants and was bordered by two guard rows planted with the same potato cultivar (Fig. 6.1).

6.2.4 Plant physiological characteristics and biomass partitioning measurements

Gaseous exchange was measured once on 23rd February, 2011 (120 DAE), by using a CIRAS-2 Portable Photosynthesis System (V2.01), in order to determine leaf stomata conductance (m $molCO_2$ m^2 s^{-1}); net photosynthesis (µmol CO_2 m^2 s^{-1}); transpiration rate (m $molH_2O$ m^2 s^{-1}) and internal Co_2 concentration (ppm), detailed in Chapters 3 and 4.

The above-ground (leaves and stems) and below-ground biomass (roots and tubers) were sampled on 28th February 2011, 125 DAE to determine the effect of leaf canopy manipulation on partitioning of dry matter to leaves, stems, roots or stolons and tubers. One small and one large plant sample was randomly uprooted from each plot using a spade. They were partitioned into leaves, stems, roots and tubers and then weighed and oven dried at 70^{o}C, until there was further weight loss. The contribution of each component to total biomass on dry matter basis was determined as the ratio of each partition to total biomass (leaves, stems, roots and tubers); per plant (Geremew *et al.*, 2007). The HI was calculated as the ratio of total tuber dry matter to total biomass on dry matter basis from the samples of each plot (Mackerron *et al.*, 1985).

Leaf area, plant height (cm) and number of stems and their diameter (mm) were measured at physiological maturity. Potato psyllid were visually scored on a scale of 0-5, with 0 representing no infection and 5 being the highest infections, per experimental unit, on 14th March, 2011 (Puketapu, 2010; Roskruge *et al.*, 2010). Leaf area was determined using a leaf area meter. Volumetric soil moisture was monitored using a TDR, model 1502C, Tektronix Inc., Beaverton, OR, USA), described in previous chapters.

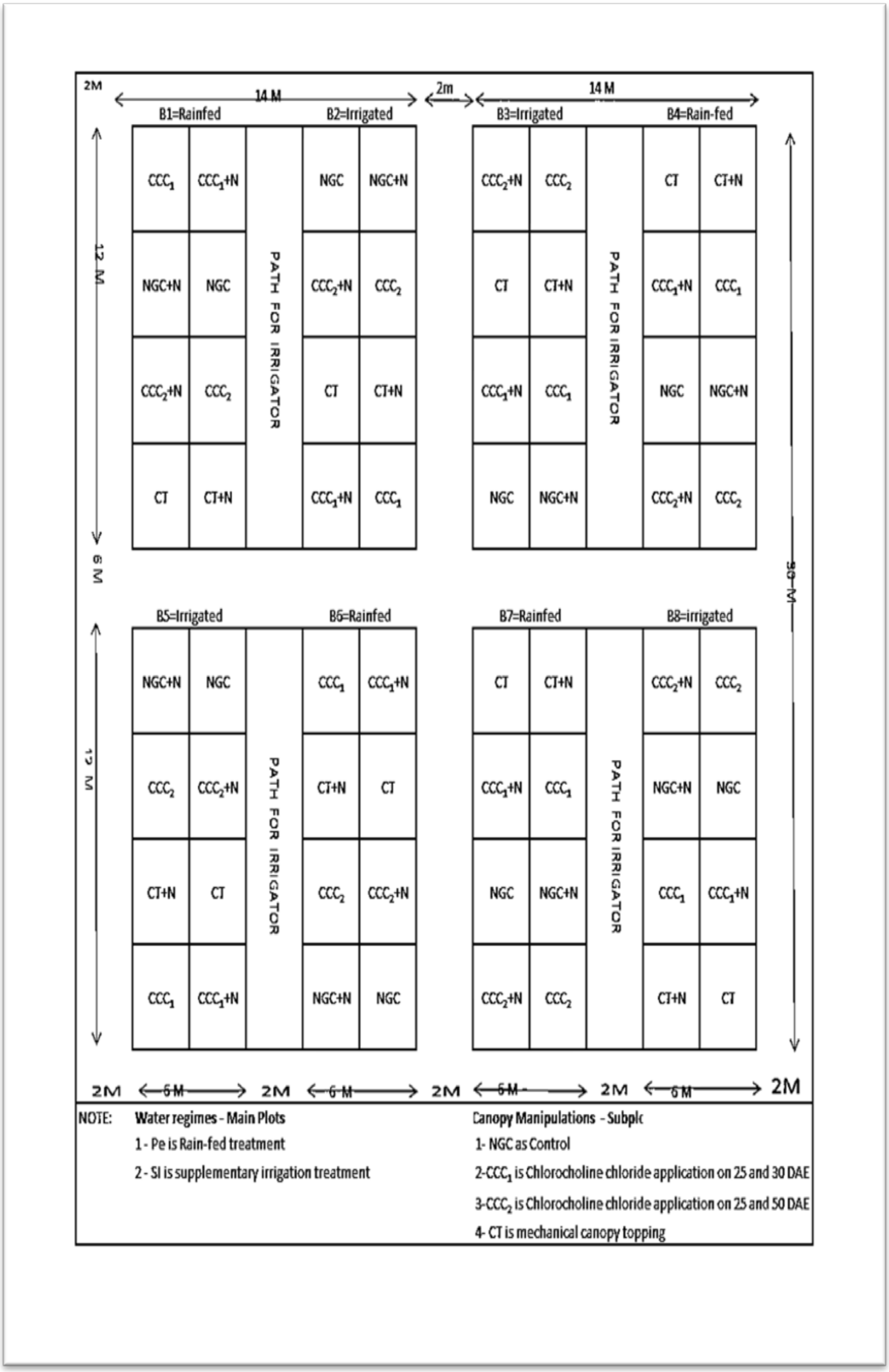


Figure 6.1 Schematic diagram for Field Experiment 4 on canopy manipulation

6.2.5 Potato tuber yield and statistical analyses

Data on plant height, number of stems and branches per plant and their diameter (mm), leaf area, number of tubers per plant, mean tuber weight and total tuber weight, marketable tuber yield and tuber dry matter content, were measured at harvest. These data and those on the physiological characteristics were analysed with the GLM procedure of the SAS (SAS, 2008); differences amongst treatment means were compared by the LSD, at the 5% probability level (Meier, 2006).

The RCBD Split-Split-plot linear statistical model used in GLM procedure was as follows:

$$\text{¥ijk} = \mu + \hat{I}_i + \beta_j + (\hat{I}\beta)_{ij} + \alpha_k + (\hat{I}\alpha)_{ik} + (\beta\alpha)_{jk} + (\hat{I}\beta\alpha)_{ijk} + \text{Ę}_{ijk};$$

Where, μ is the overall mean; $\hat{I}_i$, β_j, $(\hat{I}\beta)_{ij}$ represents the whole plot as water regimes, block and whole plot error effects; α_k, $(\hat{I}\alpha)_{ik}$, $(\beta\alpha)_{jk}$ represents subplots, as canopy manipulation effects, block effects and subplot errors; $(\hat{I}\beta\alpha)_{ijk}$ represents whole plot and subplot interaction effects; and Ę_{ijk} represents overall error, respectively, whilst i= 1-2 water regimes, j=1-4 replicates and k=1-4 canopy manipulations.

(a) Mechanical canopy topping

(b)Size of shoots topped

Plate 6.1 : Mechanical canopy topping in Tutaekuri, *Solanum tuberosum ssp. andigena in* 2010/2011

6.3. Results

6.3.1 Evapotranspiration of Tutaekuri

The Tutaekuri growing season was 170 days, with a potential crop water requirement of 590 mm (Table 6.1). A seasonal precipitation of 368 mm contributed 63% of the total crop water requirement. Consequently, the potential crop water requirement, to be met by irrigation was 278 mm. The ratio of actual water use over potential evapotranspiration per crop stage indicated water stress in the rain-fed treatment, at the vegetative (64%), development (52%) and mid-stages (65%), whilst the establishment and maturity stages (90%) had the same water use as seen in irrigated treatments (Table 6.6).

Table 6.1 Potential crop evapotranspiration (ETp), precipitation (P_e), irrigation (I), deep percolation (D_p), soil moisture change (ΔS), actual evapotranspiration (ETc) [$ETc = Pe + I - Dp + \Delta S$] in mm, per crop stage of a Taewa cultivar, Tutaekuri

Crop stages (Duration in days)	Establishment stage 20	Vegetative stage 46	Development stage 31	Mid-stage 54	Maturity stage 18	Totals Days 169
Irrigation						
ETp (mm)	21.7	170.4	134.5	208.3	54.9	589.7
Rainfall (mm)	7	93.4	70.8	134.8	62	368.0
Irrigation (mm)	0	50	78.3	52.2	0	180.5
Dp (mm)	0	0	0	0	13.3	13.3
Δs (mm)	0	13.9	0	0	0	13.9
Actual WU (ET_c)	7	157.3	149.1	187	48.7	549.1
Rain-fed						
ET_p (mm)	21.7	170.4	134.5	208.3	54.9	589.7
Rainfall (mm)	7.0	93.4	70.8	134.8	62.0	368.0
Dp (mm)	0	0	0	0	0.0	0.0
Δs (mm)	0.0	15.2	0.0	0.0	0.0	15.2
Actual WU (ET_c)	7.0	108.6	70.8	134.8	62.0	383.2

The actual water use varied with canopy manipulation ($P<0.01$) and water regime treatments ($P<0.0001$), but not between N treatments ($P>0.05$, Table 6.6). The mean actual water use for irrigation was 5490 (m^3 ha^{-1}), whilst rain-fed used 3830 (m^3 ha^{-1}). Amongst the canopy manipulation treatments, the mechanical topping had the highest water use, although it was not different from the 25-30CCC schedule, which was not different from the 25-50CCC schedule. The control used the least amount of water, although it was not different from the 25-50CCC schedule ($P>0.05$, Table 6.6).

6.3.2 Volumetric soil moisture (%)

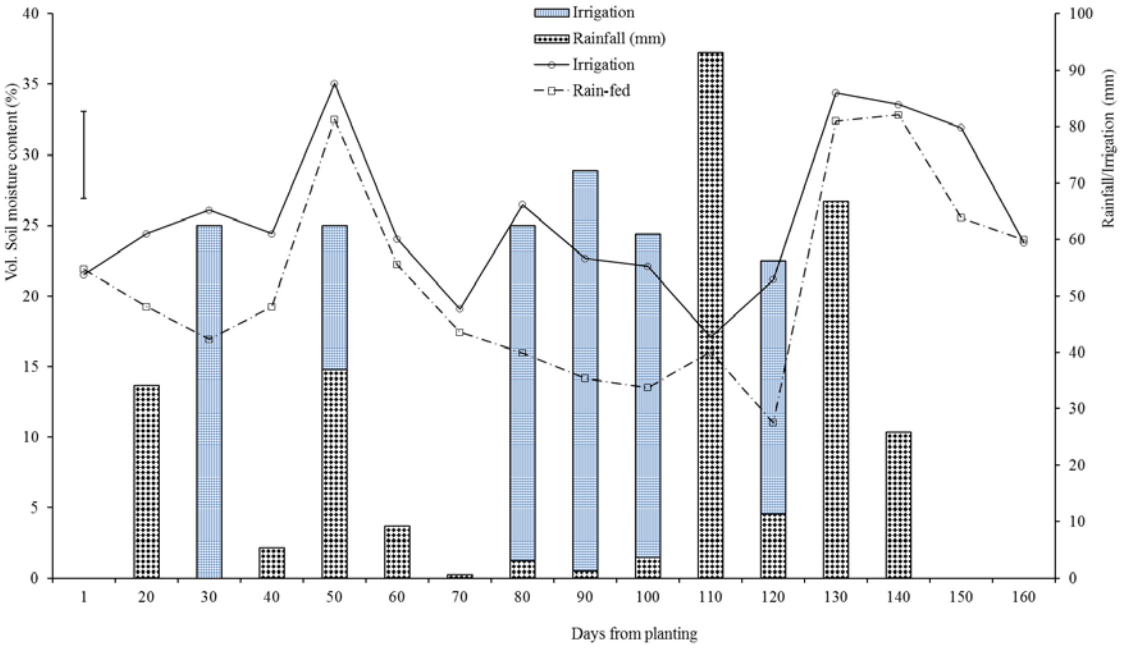


Figure 6.2 Change in volumetric soil moisture (%) during the growing season in Tutaekuri, 2010/2011. Error bar represents ±SEM.

Volumetric soil moisture content (%) was significantly influenced by water regime ($P<0.0001$) and days after planting (DAP) ($P<0.0001$, Fig. 6.2). Irrigation increased the volumetric soil moisture content ($P<0.05$), but N and canopy manipulation had no much effect on soil moisture content ($P>0.05$). Significant interactions with soil moisture were observed between water regime*DAP ($P<0.001$, Fig. 6.2). Figure 6.2 shows that the interaction in soil moisture, between DAP and water regimes, was a result of differences in water inputs on different days. The greatest depletion in soil moisture was from Days 60 to 120 after planting, in both irrigated and rain-fed. However, rain-fed had the lowest soil moisture. The days of water deficits correspond to the vegetative, development and mid-stages shown in Table 6.1, when the rain-fed crop was greatly water stressed. Drought during this period decreased soil moisture in both irrigated and rain-fed treatments.

6.3.3 Photosynthetic water use efficiency and gaseous exchange

Gaseous exchange was significantly affected by water and N regimes ($P<0.05$; Table 6.2), but not by canopy manipulations ($P>0.05$). Irrigation significantly increased net photosynthesis (A_n) ($P<0.0001$), stomatal conductance (g_s) ($P<0.0001$) and transpiration rate (T) ($P<0.001$), whilst it reduced leaf temperature (LT) ($P<0.01$). Photosynthetic water use efficiency (photosyntheitic WUE), defined as the ratio of A_n to T, was not influenced by either water regime or canopy manipulations ($P>0.05$), but it was influenced by N ($P<0.05$). However, photosynthetic WUE was highest under irrigation, where the canopy was topped or sprayed with CCC at Days 25 to 30. Exclusion of N reduced photosynthetic WUE ($P<0.05$), A_n, g_s and T ($P<0.01$) (Table 6.2).

The relationship of photosynthetic WUE to A_n, gs, T, LT and Ci, was explored, by using simple correlation. With all data combined, correlation between photosynthetic WUE and A_n ($r = 0.78$), g_s ($r = 0.45$) and T ($r = 0.51$) were generally positive ($P<0.0001$). However, photosynthetic WUE negatively correlated with LT ($r = - 0.65$) and Ci ($r = - 0.94$) (Appendix 6.2).

Table 6.2 Effect of leaf area manipulation, water and nitrogen regimes on gaseous exchange in Taewa cultivar Tutaekuri

Treatments	Photosynthetic WUE (µmolCO_2/(m molH_2O)	Net photosynthesis (µmolCO_2 m^2 s^{-1})	Stomata conductance (µmolCO_2 m^2 s^{-1})	Transpiration rate (m molH_2O m^2 s^{-1})	Internal Co_2 concentration (ppm)	Leaf temperature (C^o)
Canopy manipulation						
25-30 CCC	3.9	11.0	108.7	2.6	192.5	29.4
25-50 CCC	3.3	11.4	136.3	3.0	225.9	29.5
Topping	3.9	11.2	115.4	2.8	193.4	29.1
Control	3.7	10.9	109.7	2.6	207.3	29.6
Significance	Ns	Ns	Ns	Ns	Ns	Ns
Water regimes						
Irrigation	3.9	13.4^{b}	150.9^{a}	3.3	203.4	28.9^{b}
Rain-fed	3.5	8.9^{b}	84.0^{b}	2.2	206.1	29.8^{a}
Significance	Ns	$P<0.0001$	$P<0.0001$	$P<0.001$	Ns	$P<0.01$
Nitrogen (kg ha^{-1})						
0	3.5^{b}	9.6	99.7^{b}	2.4	213.6	29.2
140	4.0^{a}	12.7	135.3^{a}	3.1	195.8	29.3
Significance	$P<0.05$	$P<0.01$	$P<0.01$	$P<0.01$	Ns	Ns

Note : Column rows with similar letters are not significantly different at 5% level of probability

6.3.4 Vegetative plant growth characteristics

Canopy manipulation significantly affected plant height ($P<0.0001$), the number of branches per plant ($P<0.01$) and LAI ($P<0.001$), but it did not affect the number of stems per plant, stem diameter and potato psyllid score ($P>0.05$; Table 6.3). Mechanical topping of the canopy significantly reduced plant height, whilst application of CCC on different days reduced it intermediately, compared to the control which had the greatest plant height (Table 6.3). However, mechanical topping increased the number of branches per plant, whilst the growth regulator reduced it. Both mechanical topping and the two CCC application schedules decreased LAI (Table 6.3).

Table 6.3 Effect of leaf area manipulation on vegetative plant growth characteristics in Tutaekuri at physiological maturity, 2010/2011

Treatments	Plant height (cm)	Stems/ Plant	Branches/ Plant	Stem Diameter (mm)	LAI	Late blight Scores
Canopy Manipulation						
25-30 CCC_1	73.4^{b}	3.3	9.9^{b}	15.2	11.6^{b}	1.3
25-50 CCC_2	66.0^{c}	4.7	14.8^{b}	13.9	7.4^{b}	1.8
Topping	55.5^{d}	3.9	21.1^{a}	15.6	8.6^{b}	1.3
Control	92.3^{a}	2.7	12.1^{b}	15.7	16.5^{a}	0.9
Significance	$P<0.0001$	Ns	$P<0.01$	Ns	$P<0.001$	Ns
Water regimes						
Irrigation	72.6	3.5	13.4	16.4^{a}	10.5	2.3^{a}
Rain-fed	70.9	3.8	15.6	13.9^{b}	11.5	0.3^{b}
Significance	Ns	Ns	Ns	$P<0.01$	Ns	$P<0.0001$
Nitrogen (kg ha^{-1})						
0	67.5^{b}	3.9	12.8	14.9	6.9^{b}	1.3^{b}
140	76.2^{a}	3.4	16.2	15.3	15.1^{a}	1.4^{a}
Significance	$P<0.0001$	Ns	Ns	Ns	$P<0.0001$	$P<0.001$

Note: 25-30 chlorocholine chloride refers application at day 25 and 30 after plant emergence and, 25-50 chlorocholine chloride refers application at day 25 and 50 after plant emergence.

Water regimes influenced stem diameter ($P<0.01$) and potato psyllid ($P<0.0001$), but did not affect average plant height, number of stems, branches and LAI per plant ($P>0.05$; Table 6.3). Nitrogen increased plant height ($P<0.0001$), LAI ($P<0.001$) and potato psyllid ($P<0.001$), but it did not affect the average number of stems, branches and stem diameter per plant ($P>0.05$). Irrigation increased the stem diameter and incidences of potato psyllid, whereas N exclusion decreased plant height ($P<0.0001$), potato psyllid incidences ($P<0.001$) and LAI ($P<0.0001$), compared to where N was applied (Table 6.3). Nitrogen did not affect the number of stems and branches per plant, or stem diameter.

6.3.5 Dry matter production and partitioning

There were significant differences between canopy manipulation treatments in the partitioning of fresh and dry matter to the leaf ($P<0.0001$, $P<0.01$), stem ($P<0.01$, $P<0.05$), roots (Ns, $P<0.05$), tuber ($P<0.0001$, $P<0.05$) and total biomass ($P<0.05$, Ns), in addition to HI ($P<0.0001$, Table 6.4). Noticeably, partitioning to the roots did not differ on a fresh weight basis, whilst total biomass production per plant did not vary on a dry matter basis ($P>0.05$; Table 6.4). Application of CCC at two schedules and mechanical topping reduced leaf fresh and dry matter production, compared to the control. However, the greatest reduction was observed in the 25-50CCC schedule. The 25-30CCC and 25-50CCC treatments reduced stem fresh and dry matter production, the lowest being in 25-50CCC. Root dry matter production was significantly increased by mechanical topping (compared to the control) ($P<0.05$), although it was not different from 25-30CCC, which was also greater than the control and 25-50CCC treatment.

Tuber fresh and dry matter production per plant was strongly influenced by 25-50CCC, 25-30CCC and mechanical topping, compared to the control, which had the lowest tuber fresh or dry matter production ($P<0.0001$, $P<0.05$; Table 6.4). The effect of CCC application in enhancing tuber production, compared to above-ground biomass, was confirmed by the way in which the CCC application significantly increased HI compared to the control ($P<0.0001$), after 125 DAE (Table 6.4). The 25-30CCC and 25-50CCC treatment and the mechanical topping affected HI similarly. The HI, under mechanical topping, was less than 25-50CCC ($P<0.0001$), but greater than the control.

Table 6. 4 Effect of leaf area manipulation on dry matter production and partitioning per plant in Tutaekuri after 125 day emergence, 2011

Treatments	Leaf (g)		Stem (g)		Roots/Stolons (g)		Tuber (g)		Total Biomass (g)		Harvest Index (HI%)
	Fresh Weight	Dry Weight	Fresh Weight	Dry Weight	Fresh Weight	Dry Weight	Fresh Weight	Dry Weight	Fresh Weight	Dry Weight	
Canopy Manipulation (n=16)											
25-30 CCC	581.7^{b}	105.1^{b}	606.9^{b}	109.2^{ba}	117.2	24.7^{ba}	884.8^{a}	217.3^{ba}	2190.6^{ab}	456.4	47.6^{ba}
25-50 CCC	509.3^{b}	84.3^{b}	477.1^{b}	86.6^{b}	113.9	20.7^{b}	960.7^{a}	248.2^{a}	2061.1^{b}	439.8	56.4^{a}
Topping	625.6^{b}	120.4^{b}	793.8^{a}	127.2^{a}	151.3	29.2^{a}	863.7^{a}	223.3^{ba}	2434.5^{a}	500.2	44.6^{bc}
Control	872.4^{a}	168.6^{a}	808.4^{a}	114.2^{ba}	115.9	21.4^{b}	651.9^{b}	180.2^{c}	2448.7^{a}	484.4	37.2^{c}
Significance	$P<0.0001$	$P<0.01$	$P<0.01$	$P<0.05$	Ns	$P<0.05$	$P<0.0001$	$P<0.05$	$P<0.05$	Ns	$P<0.0001$
Water regimes (n=32)											
Irrigation	677.9	128.4	752.0^{a}	119.3	128.4	24.3	930.6^{a}	239.8^{a}	2488.8^{a}	511.8^{a}	46.9
Rain-fed	616.6	110.8	591.1^{b}	99.3	120.9	23.9	750.0^{b}	194.7^{b}	2078.6^{b}	428.6^{b}	45.4
Significance	Ns	Ns	$P<0.0001$	Ns	Ns	Ns	$P<0.01$	$P<0.01$	$P<0.01$	$P<0.01$	Ns
Nitrogen (kg ha^{-1}) (n=32)											
0	532.9^{b}	103.0^{a}	508.3^{b}	92.2^{b}	127.1	24.5	889.4	232.5	2057.7^{b}	453.2	51.3^{a}
140	761.5^{a}	135.3^{a}	834.8^{a}	126.4^{a}	122.1	23.5	791.3	202.0	2509.7^{a}	487.2	41.5^{b}
Significance	$P<0.001$	$P<0.05$	$P<0.001$	$P<0.01$	Ns	Ns	Ns	Ns	$P<0.001$	Ns	$P<0.001$

Irrigation enhanced tuber production ($P<0.01$) and total biomass production (fresh and dry weight basis) ($P<0.01$) and fresh stem biomass production per plant 125 DAE ($P<0.0001$; Table 6.4). Conversely, water regime had no effect on leaf and root fresh or dry matter production, stem dry matter and HI ($P>0.05$). There were also significant differences between complete exclusion of N application and application of N. Application of N extensively increased partitioning to the fresh and dry leaves ($P<0.0001$, $P<0.05$), stem ($P<0.001$, $P<0.01$) and total fresh biomass production ($P<0.001$, Ns), respectively and it significantly reduced HI ($P<0.001$). However, N had no effect on tuber and root fresh and dry matter production per plant ($P>0.05$).

The 25-50CCC schedule resulted in 58% of assimilates partitioned to the tuber, whilst 25-30CCC and mechanical topping partitioned 48% of dry matter to the tubers. The control only allocated 26% to the tubers and the remainder to leaf (32%), stem (24%) and roots (19%), after 125 days from planting. The addition of N decreased allocation to the tubers by 32% (25-30CCC), 13% (25-50CCC), 11% (mechanical topping) and 36% in the control. Exclusion of N in Tutaekuri production reduced partitioning of dry matter to the leaves and stem, whilst it increased tuber proportion (Table 6.4).

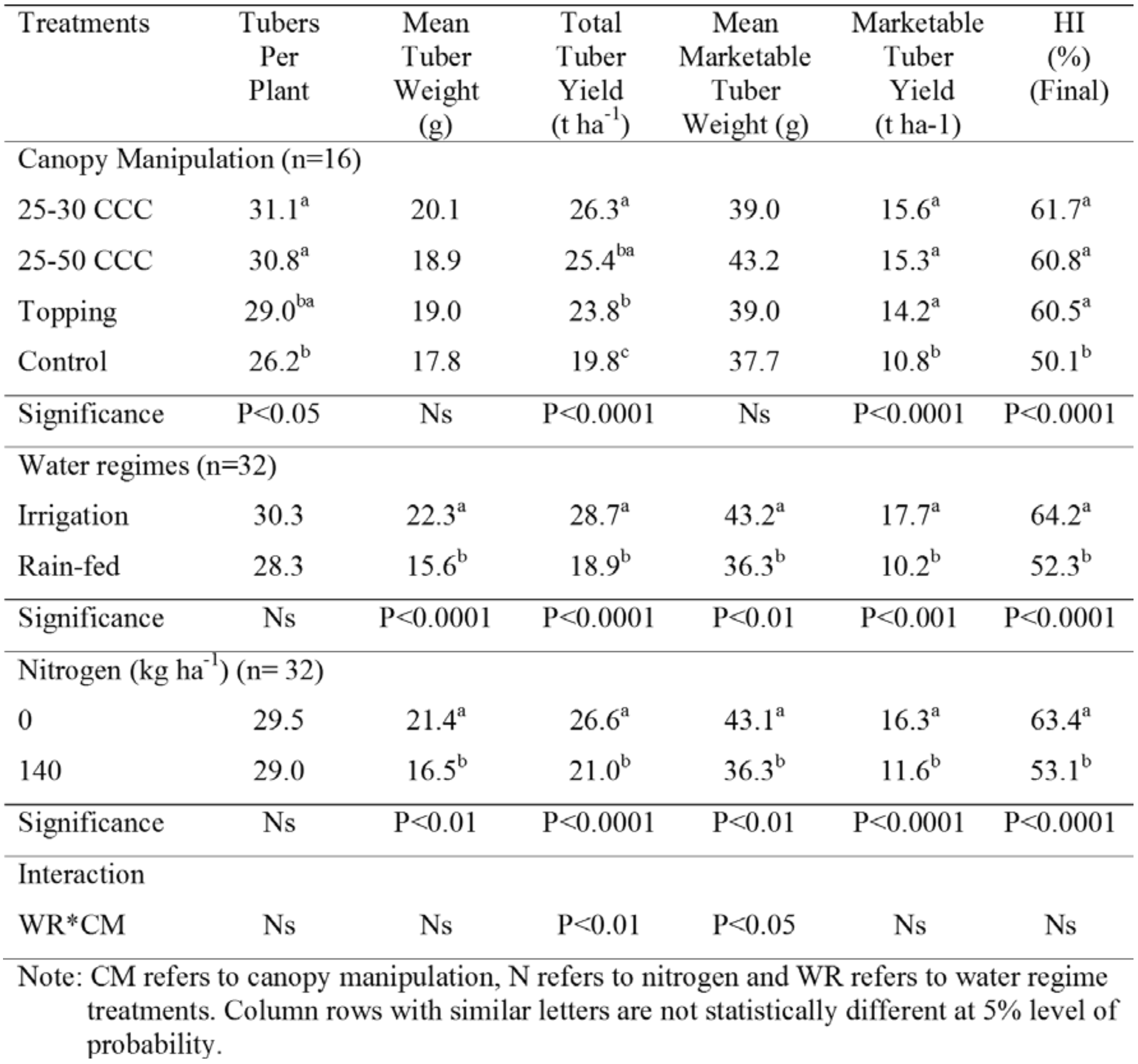
6.3.6 Tuber yield and yield components at final harvest

Canopy manipulation strongly affected total tuber yield ($P<0.0001$), marketable tuber yield ($P<0.0001$), number of tubers per plant ($P<0.05$), and final HI ($P<0.0001$; Table 6.5). However, it did not affect mean tuber weight for total and marketable yield ($P>0.05$). The 25-30CCC and 25-50CCC schedules had the highest total tuber yield, with 25-30CCC being greater than mechanical topping, but not 25-50CCC (Table 6.5). Mechanical topping was intermediate for total tuber yield, although not different from 25-50CCC. Marketable tuber yield and HI were not different between mechanical topping, 25-30CCC and 25-50CCC, with 25-30CCC being greater than mechanical topping and 25-50CCC. The control had the lowest total tuber yield (t ha^{-1}), marketable tuber yield (t ha^{-1}), number of tubers per plant, and final HI. Canopy management greatly improved marketable tuber yield by 32 - 44%, compared to 20 - 32.8% increase on total tuber yield (Table 6.5).

Irrigation increased mean tuber weight ($P<0.0001$), total tuber yield ($P<0.0001$), mean marketable tuber weight ($P<0.01$), marketable tuber yield ($P<0.001$) and final HI

($P<0.0001$), but did not affect the number of tubers per plant ($P>0.05$, Table 6.5). The mean tuber weight (g), total tuber yield, mean marketable tuber weight (g), marketable tuber yield and final HI, were increased by 43%, 52%, 19%, 74% and 23% with irrigation, respectively. On the contrary, N decreased the mean tuber weight ($P<0.01$), total tuber yield ($P<0.0001$), final HI at harvest ($P<0.0001$), mean marketable tuber weight ($P<0.01$) and marketable tuber yield ($P<0.0001$). The number of tubers per plant was not influenced by N. Nitrogen decreased the mean tuber weight (g), total tuber yield, mean market tuber weight (g), marketable tuber yield, and final HI by 30%, 27%, 19%, 19% and 41%, respectively.

Table 6.5 Average tuber per plant, mean tuber weight (g), total and marketable tuber yield and final HI for Tutaekuri under different water and N regimes, 2010/2011



Treatments	Tubers Per Plant	Mean Tuber Weight (g)	Total Tuber Yield (t ha^{-1})	Mean Marketable Tuber Weight (g)	Marketable Tuber Yield (t ha-1)	HI (%) (Final)
Canopy Manipulation (n=16)						
25-30 CCC	31.1^{a}	20.1	26.3^{a}	39.0	15.6^{a}	61.7^{a}
25-50 CCC	30.8^{a}	18.9	25.4^{ba}	43.2	15.3^{a}	60.8^{a}
Topping	29.0^{ba}	19.0	23.8^{b}	39.0	14.2^{a}	60.5^{a}
Control	26.2^{b}	17.8	19.8^{c}	37.7	10.8^{b}	50.1^{b}
Significance	$P<0.05$	Ns	$P<0.0001$	Ns	$P<0.0001$	$P<0.0001$
Water regimes (n=32)						
Irrigation	30.3	22.3^{a}	28.7^{a}	43.2^{a}	17.7^{a}	64.2^{a}
Rain-fed	28.3	15.6^{b}	18.9^{b}	36.3^{b}	10.2^{b}	52.3^{b}
Significance	Ns	$P<0.0001$	$P<0.0001$	$P<0.01$	$P<0.001$	$P<0.0001$
Nitrogen (kg ha^{-1}) (n= 32)						
0	29.5	21.4^{a}	26.6^{a}	43.1^{a}	16.3^{a}	63.4^{a}
140	29.0	16.5^{b}	21.0^{b}	36.3^{b}	11.6^{b}	53.1^{b}
Significance	Ns	$P<0.01$	$P<0.0001$	$P<0.01$	$P<0.0001$	$P<0.0001$
Interaction						
WR*CM	Ns	Ns	$P<0.01$	$P<0.05$	Ns	Ns

Note: CM refers to canopy manipulation, N refers to nitrogen and WR refers to water regime treatments. Column rows with similar letters are not statistically different at 5% level of probability.

There was a significant interaction between irrigation and canopy manipulation on total tuber yield (P<0.01, Fig. 6.3) and on mean marketable tuber weight (P<0.05). There was a rapid decrease in tuber yield for 25-50CCC, from the highest under irrigation to the lowest under rain-fed conditions, amongst the three canopy manipulations, whereas the tuber yield decrease from mechanical topping and 25-30CCC were constant and small. Mechanical topping and 25-30CCC performed better than 25-50CCC, under rain-fed (Fig. 6.3)

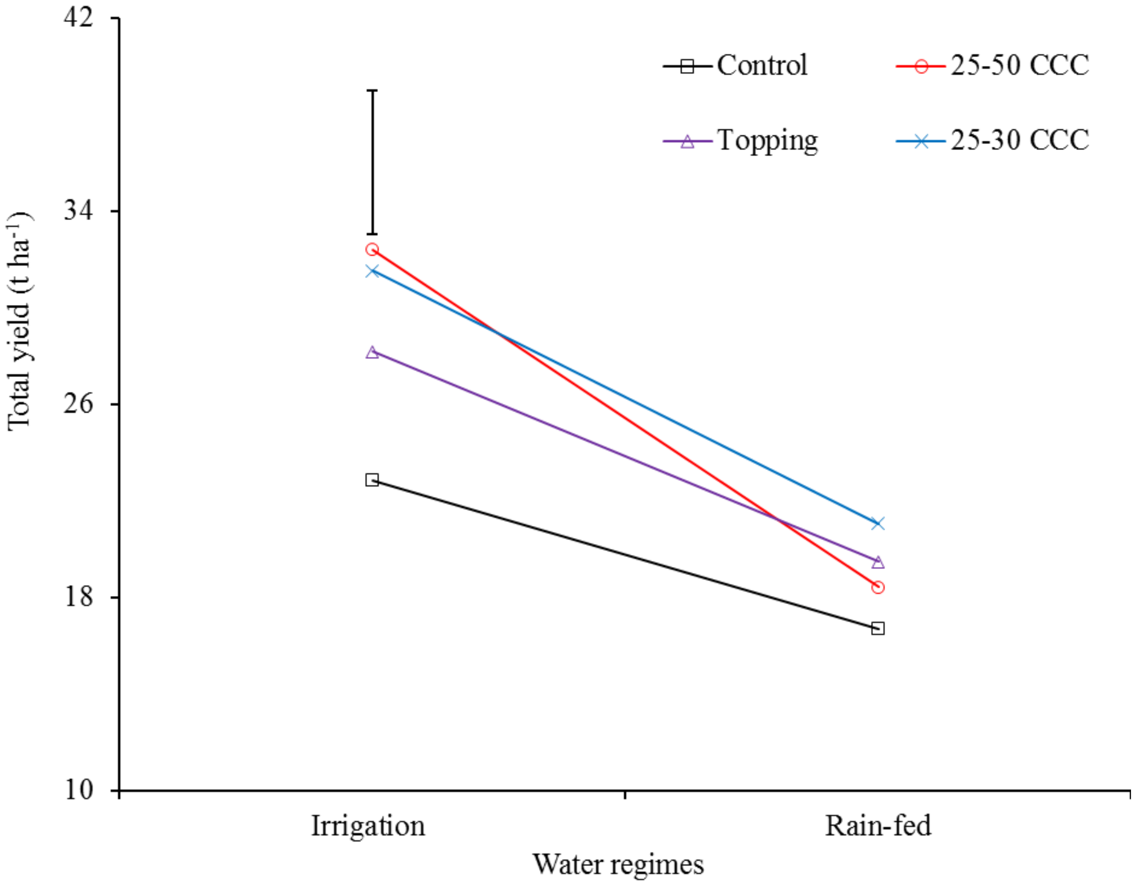
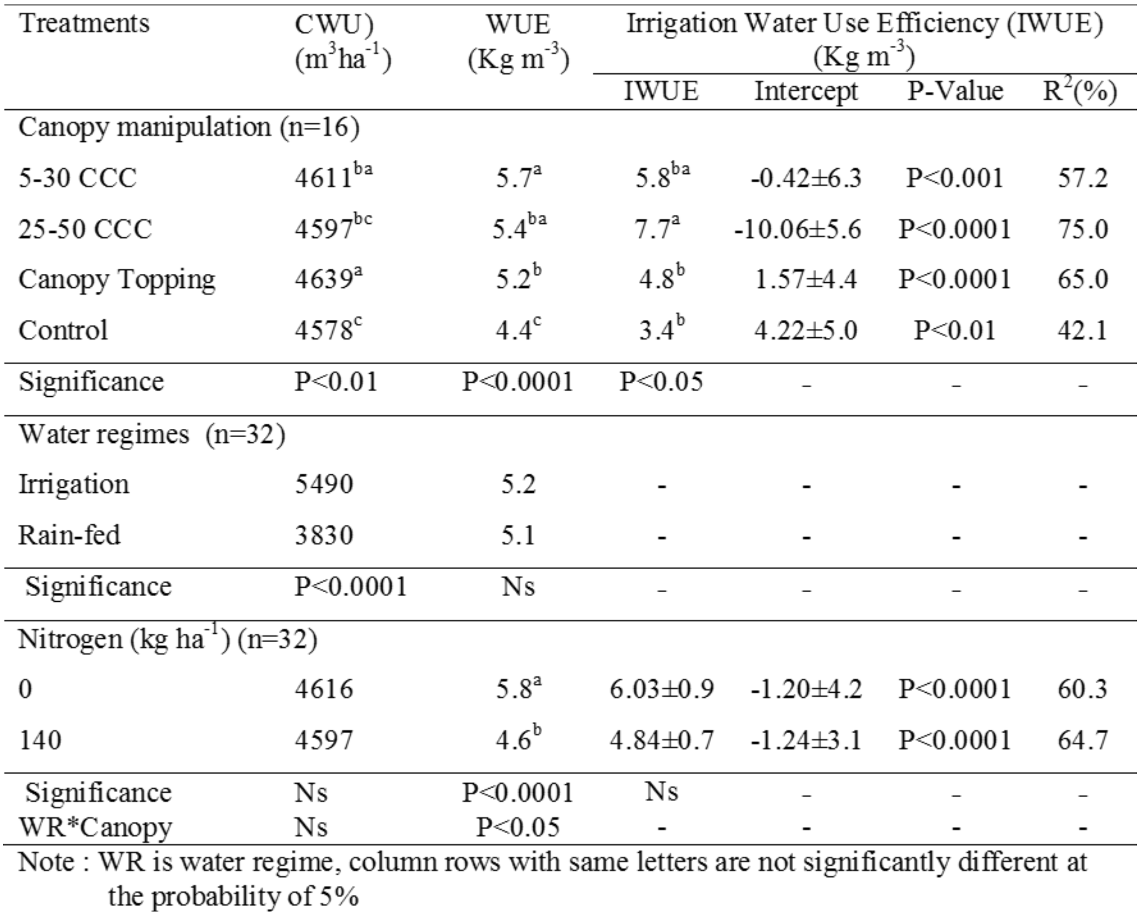


Figure 6.3 Interaction between water regimes and canopy manipulation on total yield. Error bar represents ±SEM.

6.3.7 Water use efficiency and irrigation water use efficiency

Water use efficiency (Kg ha^{-1} m^{-3}) determined as the ratio of total tuber yield (t ha^{-1}) to actual crop water use (m^{3}ha^{-1}) reflected tuber yield and water use. It was highest in 25-30CCC, which was significantly higher than the control and mechanical topping (P<0.0001) (Table 6.6). Mechanical topping was intermediate, but significantly different from the control and smaller than 25-50CCC. The modification of canopy through 25-30CCC, 25-50CCC and mechanical topping, respectively, increased WUE by 30%, 23% and 18%, compared to the control (Table 6.6). Water use efficiency was not significantly influenced by irrigation ($P>0.05$), but it was influenced by N ($P<0.0001$). Application of N, as a side dressing after 24 DAE, reduced WUE by 26%, compared to treatments without N (Table 6.6). There was an interaction between irrigation and canopy manipulation on WUE ($P<0.05$, Fig. 6.4). Mechanical topping and 25-30CCC had similar WUE between irrigation and rain-fed treatments, whilst 25-50CCC decreased relatively more under rain-fed environment, thus resulting in the interaction for WUE, which reflected the total tuber yield trend (Fig. 6.4).

Table 6.6 Effect of canopy manipulation on crop water use (CWU); water use efficiency (WUE); and irrigation water use efficiency (IWUE) for Tutaekuri, 2011



Treatments	CWU) (m^3ha^{-1})	WUE ($Kg\ m^{-3}$)	Irrigation Water Use Efficiency (IWUE) ($Kg\ m^{-3}$)			
			IWUE	Intercept	P-Value	R^2(%)
Canopy manipulation (n=16)						
5-30 CCC	4611^{ba}	5.7^{a}	5.8^{ba}	-0.42±6.3	$P<0.001$	57.2
25-50 CCC	4597^{bc}	5.4^{ba}	7.7^{a}	-10.06±5.6	$P<0.0001$	75.0
Canopy Topping	4639^{a}	5.2^{b}	4.8^{b}	1.57±4.4	$P<0.0001$	65.0
Control	4578^{c}	4.4^{c}	3.4^{b}	4.22±5.0	$P<0.01$	42.1
Significance	$P<0.01$	$P<0.0001$	$P<0.05$	-	-	-
Water regimes (n=32)						
Irrigation	5490	5.2	-	-	-	-
Rain-fed	3830	5.1	-	-	-	-
Significance	$P<0.0001$	Ns	-	-	-	-
Nitrogen ($kg\ ha^{-1}$) (n=32)						
0	4616	5.8^{a}	6.03±0.9	-1.20±4.2	$P<0.0001$	60.3
140	4597	4.6^{b}	4.84±0.7	-1.24±3.1	$P<0.0001$	64.7
Significance	Ns	$P<0.0001$	Ns	-	-	-
WR*Canopy	Ns	$P<0.05$	-	-	-	-

Note : WR is water regime, column rows with same letters are not significantly different at the probability of 5%

Mean IWUE was 5.5 kg m^{-3} (r^2= 52%) with all data combined. With data stratified by canopy manipulation, IWUE was greatest in 25-50CCC and lowest in the control (Table 6.6). For data stratified by N treatment, IWUE decreased from 6.0 to 4.8 (kg m^{-3}) with N application (Table 6.6).

6.4 Discussion

6.4.1 Photosynthetic WUE and gaseous exchange

The results for photosynthetic WUE and gaseous exchange indicated greater stomatal resistance with water and N deficit, regardless of canopy manipulation. This was demonstrated by improvement in $A_{n,}$ $g_{s,}$ and T with irrigation and N, whereas water stress and zero N decreased photosynthetic WUE, $A_{n,}$ $g_{s,}$ and T in Tutaekuri, as once reported by Olesinski *et al.* (1989). Water and N deficit effects on Tutaekuri were highly related to stomatal resistance, as a restricting factor to photosynthetic WUE. The stomatal resistance increased by 80% and 36% by rain-fed and N deficit, respectively. It is probable that Tutaekuri closed stomata in order to avoid high transpiration under the rain-fed environment.

Studies show that stomatal resistance increases in potato with water and N stress, due to reduced leaf area and increased abcisic acid from roots to leaves, as a means of enduring drought, as reported under partial root zone drying (Liu *et al.,* 2006b). However, the control of the stomatal aperture did not increase photosynthetic WUE, as is expected in many plants. The possible reason for this could be the additional negative impact of high leaf temperature on photosynthesis, because gaseous exchange is also controlled by climatic factors. High leaf temperature raises atmospheric vapour pressure deficits, which then induces stomatal resistance (Sinclair *et al.,* 1984). The implication of high water vapour gradient is leaf water deficits that result in a declining A_n and T rate (Bunce, 2003). High leaf temperature brings about mesophyllic resistance to photosynthesis in potato (Wolf *et al.,* 1990).

Mesophyllic and stomatal activity, without affecting Ci, were also reported by Schapendonk *et al.* (1989) as being affected by water and N stress. The integration of stomatal and mesophyl conductance is reported to be caused by a progressive build-up in water stress that results in secondary restrictions to A_n in C3 and C4 plants (Flexas *et al.,* 2002; Ripley *et al.,* 2010). It can be presumed from the results in this study that the water deficit during the study period was very critical to the non-irrigated crops. This result supports reports by Ahmadi *et al.* (2010) and by Liu *et al.* (2006a) that water deficit is a primary limitation to potato photosynthetic capacity. Contrary to studies by Wang *et al.* (2009b) and Jones (1972), these results do not indicate supremacy in photosynthetic capacity for plants treated with CCC and mechanical topping, as reported in potato and Brussel sprout, respectively. A possible reason is that the days of gaseous exchange measurements after treatment differ from reports in the literature. Consequently, the short-term photosynthetic capacity induced by canopy manipulation might have been missed.

6.4.2 Vegetative growth and dry matter production

The application of CCC and mechanical topping improved the partitioning of dry matter assimilates to the tuber, compared to the control. A schedule of 25 - 50CCC managed to increase partitioning to the tuber by 38%, whilst 25 - 30CCC and mechanical topping, respectively, increased assimilation of dry matter to the tuber by 21% and 24%, after 125 DAE. Plants treated with CCC managed to assimilate more dry matter to the tuber than mechanical topping, by reducing LAI, plant height and number of branches. Apart from reducing excess plant height and LAI, mechanical topping concurrently increased the partitioning of dry matter to axiliary branches and stems, thereby partially reducing its allocation to tubers, compared to the level of CCC. These results agree with Jones (1972) on the effects of topping Brussel sprout and by Wang *et al.* (2010) and Radwan *et al.* (1971) on the effects of CCC application effect on potato vegetative growth and dry matter partitioning.

According to Gifford *et al.* (1981) and Marcelis (1996), the distribution of dry matter in plants is regulated by the sink. In another study by Tekalign *et al.* (2005), it was also observed that stronger sinks, such as developed berries and fruits, out-compete the tuber sink in dry matter distribution. The current study suggests that various growing shoots in Taewa have powerful sinks that result in competition with the below-ground sinks and tubers, when regulating the partitioning of assimilates. Spraying of CCC on leaves and the mechanical topping of growing shoots enhances the redirection of dry matter assimilates, from the excessive growing shoots to the tubers. Topping or pruning also enhances the redistribution of assimilates in Brussel sprout (Jones, 1972) and tomato (Heuvelink, 1997) to major sinks, whilst topping in sweet potato reduces partitioning to the tubers (Mulungu *et al.,* 2006). Growth regulators, CCC (Wang *et al.,* 2010) and paclobutrazol (Tekalign *et al.,* 2004), discourage excessive vegetative growth in potato, by inhibiting gibberellic acid, whilst mechanical topping disturbs the LAI and growing shoots. Consequently, the photoassimilates manufactured by the remaining green area increases roots dry matter, apart from increasing tuber dry matter in Tutaekuri, as observed in other *Solanum tuberosum ssp. andigena* (Kumar *et al.*, 1974).

Canopy manipulation induced Tutaekuri to respond to irrigation, through increased stem size and partitioning of dry matter to roots and tubers. However, irrigation increased the incidences of potato psyllid, compared to rain-fed treatment. Irrigation and large vegetative growth increases soil moisture and relative humidity, thereby creating a desirable micro-climate environment for pests and disease incidence (Olanya *et al.*, 2007). A study by Olanya *et al.* (2010), on the effect of irrigation and potato varieties on disease incidence, also found that irrigation increases disease prevalence, depending on the irrigation schedule and potato resistances level. However, another study on irrigation effect on late blight diseases, by Olanya *et al.* (2007), did not find a significant influence from irrigation on diseases and pest prevalence. Nevertheless, this study has indicated the influence of irrigation on potato psyllid prevalence in *Solanum tuberosum spp.andigena* (Tutaekuri). It is probable that partial irrigation scheduling (see Chapter 5) can reduce the incidence of pests and disease prevalence in *Solanum tuberosum spp.andigena* (Tutaekuri), as reported by Olanya *et al.* (2010), where proper irrigation reduced late blight and pest incidence in potatoes.

The dry matter allocation to leaves and stems increased with N application, as a side dressing, compared to when N was completely excluded. Nitrogen increased vegetative growth at the expense of tubers, resulting in low HI. It is known that N fertilisation increases above-ground dry matter accumulation and LAI in some *Solanum tuberosum ssp. andigena*, whilst it decreases NUE and HI (Zebarth *et al.*, 2008). Consequently, canopy manipulation minimised the N effect of decreasing dry matter partitioning to the tuber, through the rearrangement of assimilate distribution to the tubers. However, a combination of N and canopy management is an ideal strategy for Tutaekuri optimum translocation of assimilates to tubers in Tutaekuri.

6.4.3 Total tuber yield and yield components

The foliar application of CCC (at 2 $g\ell^{-1}$ in two schedules of 25-30CCC and 25-50CCC) and the mechanical topping at 52 DAE increased total tuber yield, marketable tuber yield and HI, compared to the control. The 25-30CCC, 25-50CCC and canopy topping increased total tuber yield by 33%, 28% and 20%, respectively. All canopy manipulation treatments achieved high tuber yield, by increasing the number of tubers per plant and HI. The increase in the number of tubers agrees with Rex (1992), whilst the total and marketable tuber yield increase with CCC, in this report, is in contrast to that of Rex, (1992). This study implies that obstruction of excessive shoot growth in Tutaekuri enhances photoassimilates partitioning into tubers, thereby boosting tuber growth (Wang *et al.,* 2009a). This finding also agrees with Kumar *et al.* (1974) and Sharma *et al.* (1998), who reported that CCC promotes tuberisation by reducing the level of gibberellins, which are reported to inhibit tuber formation and which promote vegetative growth in *Solanum tuberosum ssp. andigena.* In another study, Wanga *et al.*, (2010) established that CCC (at 2 $g\ell^{-1}$ in 25-30 schedules) increased tuber yield in potato, by improving its nutrition status. On the other hand, this study indicated that higher number of tubers per plant in modified crops than control did not affect tuber yield, which was never reported in referred studies.

The high number of tubers per plant (without decreasing tuber yield and marketable tubers between canopy manipulation treatments) suggest that there was no competition between tubers and vegetative growth on dry matter distribution. This implies that canopy manipulation strengthened the dominant sink to demand more assimilates: and assimilates were almost equally distributed between the tubers. It also means that the number of tubers per plant were not a limiting factor to dry matter allocation to tubers, due to canopy manipulation. Studies on fruit load in tomato have indicated that an increase in fruit load decreases the fruit weight and total yield, as a result of competition between fruit for assimilates (Heuvelink, 1997). The low tuber weight and tuber yield in the control, despite it having a low number of tubers per plant in this study, confirms that the number of tubers competed with the enormous above-ground biomass for assimilates, at the expense of the tuber weight. This result suggests that the technique to improve Tutaekuri HI with regulatory hormones and mechanical topping is the mechanism to improve Taewa yield components.

Mechanical topping, physically reduced the area for assimilate distribution and it redirected the distribution of most assimilates to the tuber, in the same way as the growth regulator, CCC. However, mechanical topping of plant leaf bearing shoots enhanced prompt regrowth of branches, as survival strategies for the reduced LAI for photosynthesis. It is probable that the increase of stem or branches dry matter, following mechanical topping, contributed to low HI, compared to the CCC application. On the other hand, the induction of root assimilation above CCC treatments helped mechanical topping treatments to abstract enough water thereby equating tuber yield with CCC treatments. The weakness of mechanical topping may include exposure of the plant to diseases, due to wounds and the increased probability of plant lodging, due to multiple branching as well as determination of proper topping time and number of topping. Fungal spray, partial irrigation (see Chapter 5) and low N may reduce disease exposure in mechanically topped Taewa.

Hossain *et al.* (1992) found that topping potato at 30+45 DAP, followed by 30+60 DAP, increased the number of leaves, total leaf area, number of branches, number of tubers and tuber weight and tuber yield (32 - 35 t ha^{-1}). The crop in this study was topped at 52 DAE, which is closer to 30+60 DAP found in the Hossain study (1992), thus indicating that it will be necessary, in the near future, to assess the appropriate time for topping Tutaekuri (*Solanum tuberosum ssp. andigena*). For these reasons, both hormonal and mechanical canopy managements are realistic, in order to increase total tuber yield and marketable tuber in Taewa. However, mechanical topping is more convenient and sustainable for the majority of Maori growers, who tend to prefer more natural interventions over use of growth regulators; also, growth regulators are more expensive than mechanical topping.

Previous chapters have demonstrated that Tutaekuri tuber yield does not respond to full irrigation. The present study suggests that canopy modification induced Tutaekuri to respond to full irrigation. This supports Kumar *et al.* (1973) who reported that tuberisation in *Solanum tuberosum ssp. andigena* is regulated by specific stimuli (short-days and grafting) at active growing shoot points. The CCC and mechanical topping de-activates the factors in Tutaekuri which make it not respond to full irrigation. It is probable that mechanical topping induces mechanical resistance for ethylene production from indole-3-acetic acid (IAA) the same as CCC (Vreugdenhil, *et al.*, 1989). Ethylene increases with stress and it counteracts gibberellin negative effects on tuber formation by facilitating other hormones on tuber formation (Vreugdenhil, *et al.*, 1989). The role of irrigation and the exclusion of N were well incorporated with CCC and mechanical topping. Therefore, the increased tuber yield resulting from these treatments was a consequence of increased partitioning of assimilates to roots and tubers. This shows that Tutaekuri management can be based on an integration of canopy, irrigation and N management. However, growers need to bear in mind how the influence of canopy manipulation, on total tuber yield and marketable tuber yield, can vary with water regime and N.

The study has shown that the mean tuber yield for 25-50CCC sporadically decreased with water stress under rain-fed condition, whereas the tuber yield decrease (following mechanical topping and 25-30CCC treatments) were constant and minimal. The way in which tuber declined in 25-50CCC with water stress caused the interaction relating to tuber yield. This suggests that 25-50CCC is not as effective as mechanical topping and 25-30CCC, under water stress. The 25-50CCC schedule is recommended for irrigated conditions, whilst mechanical topping and 25-30CCC suit both environments. A possible reason for this finding is that mechanical topping and 25-30CCC induced root development, which helped both to extract more water and withstand water stress, compared to the control and 25-50CCC.

6.4.4 Crop water use, WUE and irrigation water use efficiency

Plants whose leaf canopies were modified consumed more water, whilst increasing WUE and IWUE during the growing season, compared to the control. The 25-30CCC and mechanical topping treatments used more water, due to well- developed roots, upon which potato water uptake depends (Stallham *et al.,* 2004). The ratio of actual water use to potential evapotranspiration for canopy manipulation (76%) illustrates low water use in the control (74%). Similarly, rain-fed treatments (63%) indicate that the irrigated treatment (93%) maintained water consumption closer to potential evapotranspiration, which is regarded as critical for maximum yield in potato (Ferreira *et al.,* 2007). The failure of rainfall to meet Tutaekuri water requirement can be fully observed in the critical stages (vegetative, development and mid-stage), thus indicating at what time irrigation is greatly needed in Tutaekuri. Subsequently, plant water extraction was greatly influenced by water availability, rather than canopy manipulation.

The mean WUE varied with canopy manipulation and it ranged from 4.4 (control) to 5.7 (25-30CCC). This is below the global WUE average for potato, which ranges from 6.2 kg m^{-3} to 11.6 kg m^{-3} (FAO, 2009). However, the leaf modification improved WUE for irrigated Tutaekuri, especially with 25-30CCC, compared to the control (Fig.6.4). This schedule responded to WUE because it facilitated the partitioning of asssimilates to both roots and tuber dry matter, resulting in high WUE. On the other hand, the IWUE was highest in 25-50CCC, due to low water abstraction in relation to its low root dry matter, which allowed it to use the extra unit of irrigation water efficiently, compared with 25-30CCC and mechanical topping. However, all canopy management effectively increased WUE and IWUE in Tutaekuri.

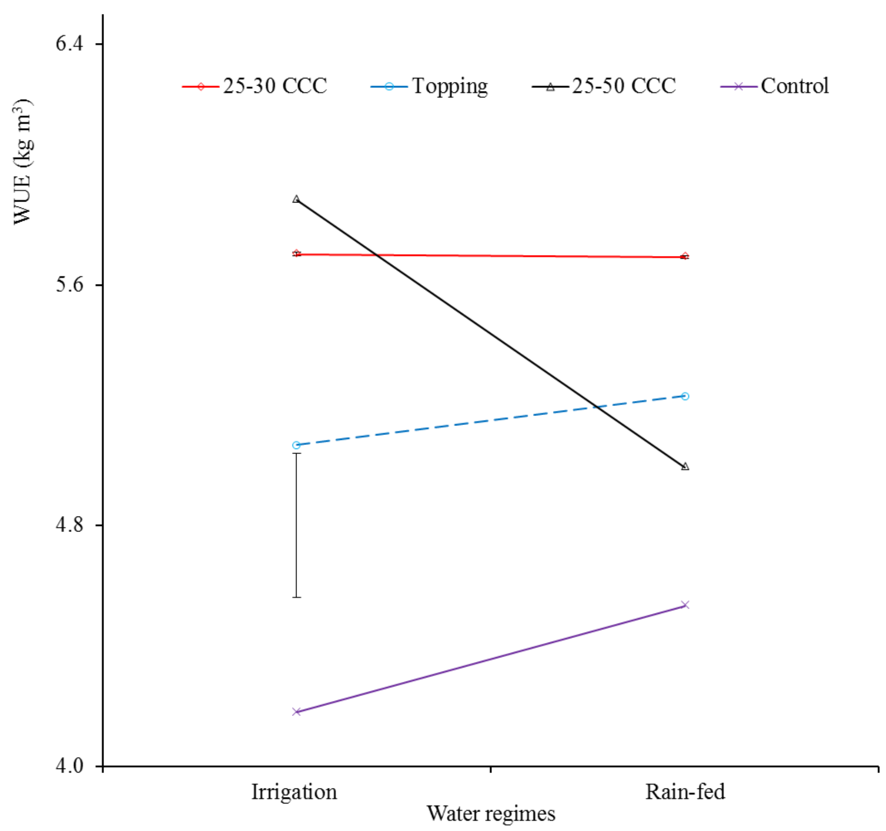


Figure 6.4 Interaction between water regime and canopy manipulation on water use efficiency (WUE) (kg m^{-3}). Error bar represents ±SEM

The behaviour of WUE in Tutaekuri between the two water regimes is surprising, because the literature reports high WUE with restricted irrigation (Battilani *et al.* 2004) and with N application (Darwish *et al.*, 2006). Contrary to these findings, WUE between irrigation and rain-fed did not vary and WUE was highest in treatments without N. Failure of Tutaekuri to optimise water under a restricted water environment indicates that *Solanum tuberosum ssp. andigena* is not very efficient in water and N use for tuber production, compared to *S. tuberosum*, due to its low yield potential (Kumar *et al.*, 2006). *Solanum tuberosum ssp. andigena* has not been bred for high WUE and NUE (Zebarth *et al.*, 2004; Zebarth *et al.*, 2008); it was the CCC and canopy topping strategies that enhanced WUE and IWUE. Water use efficiency and IWUE results confirm earlier observations that canopy manipulation induces yield and efficient water use in Tutaekuri through root development, apart from the reduced canopy for transpiration and the re-allocation of more dry matter to tubers. The significance of canopy management is that it optimises crop water use, by minimising water loss and excess vegetative growth, whilst maximising plant water uptake and tuber productivity in Tutaekuri. According to this study, selection of Tutaekuri for HI improvement is highly recommended inorder to enhance Taewa productivity in New Zealand.

6.5 Conclusion

The study has examined the consequences of mechanical topping and foliar application of growth regulator (at the rate of $2g\ell^{-1}$ on 25-30CCC and 25-50CCC schedules) and compared it with normal growth on tuber yield and WUE in Tutaekuri. The results indicate that both growth regulator schedules and mechanical topping reduced excessive vegetative growth, whilst increasing the translocation of dry matter to the tubers, compared to the control — but with different mechanisms. The 25-30CCC schedule redirected most of assimilates, which would be used for vegetative growth, to the roots and tubers, whereas mechanical topping increased both roots and tubers, whilst it increased stem or branches dry matter. The 25-50CCC schedule had the highest tuber dry matter per plant with intermediate root dry matter. Irrigation facilitated assimilation to tubers, whilst the addition of N reduced HI, due to increased and excessive vegetative growth.

The results also indicate that irrigation and N are paramount for enhancing photosynthetic WUE and photosynthetic capacity, regardless of canopy manipulation. Finally, the results suggest that the management of canopy increases the total tuber yield, WUE, and IWUE due to the redistribution of dry matter to the tuber. However, the final tuber yield depended on how each canopy management prepared the plant to use water efficiently. The 25-30CCC and mechanical topping easily helped to adapt the plant to water stress, by partitioning more assimilates to the roots, whilst the 25-50CCC delayed root development, since the second treatment was applied late and hence, it made the crop very sensitive to water stress resulting into high IWUE. Therefore 25-50CCC would be the recommended strategy for irrigated conditions, whilst all the other treatments would suit both irrigated and rain-fed conditions. It is recommended that growers should be managing the canopy of Tutaekuri, in order to optimise crop water use and tuber productivity, in New Zealand.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUSION

7.1 Introduction

Taewa and other heritage crop cultivars (e.g. Kamokamo) are important for the cultural economy of New Zealand (McFarlane, 2007). Relative to modern cultivars, heritage crops offer high premiums for growers selling in a niche market. Nevertheless, their productivity is very low, due to a lack of information on crop agronomic performance in modern production systems (Harris *et al.,* 1999; Hayward, 2002). Modern crop cultivars (such as modern potato and Buttercup squash) have been widely studied, including aspects of water and nutrient use (Craighead *et al.,* 1999). It is known that modern crops lack some of the nutritive value, processing and agronomic attributes, which are present in heritage cultivars (Lister, 2001; Singh *et al.,* 2008). The current increase in economic water scarcity (IWMI, 2000, 2002), alongside issues related to climate change in New Zealand, requires crops with premium prices and technologies with a high efficiency of resource use. Therefore, research is needed in the Asia and Pacific region (especially on potato and other crops), which focus on improving WUE through identifying crop cultivars with high WUE and management technique that lead to the greatest WUE (Pandey, 2008; Clothier *et al.,* 2010).

The literature review in Chapter 2 highlights that the strategies for improved WUE can minimise water costs and environmental degradation, whilst maximising yields in order to meet market needs, in addition to enhancing net farm income. However, Taewa and other heritage crop cultivars in New Zealand have not previously been thoroughly studied for their water and N use efficiencies. It was not scientifically known whether low yields in heritage cultivars are the result of inappropriate soil and water management, or rather simple genetics. The overall objective of this study was to compare crop performance and water use efficiency in heritage and modern cultivars in response to irrigation and N management. Therefore, the general hypothetical question was: '*What is the impact of water and N management on heritage crop cultivars compared to modern crop cultivars, in relation to crop growth pattern, yield, WUE or economic value per unit of water used?*' Four experiments were conducted: one glasshouse and three field experiments. Oca (*Oxalis tuberosa*) and pumpkin squash (C*ucurbita spp.*) were studied once, as a supplement to Taewa and modern potato, which were the main crops studied (Chapter 4).

At the beginning of the study, two Taewa (Moe Moe and Tutaekuri) and two modern potato cultivars (Moonlight and Agria) were studied in the glasshouse, at two different levels of irrigation (60% ET and 100% ET) and N (50 and 200 kg N ha^{-1}), between June and November 2009 (Chapter 3). The second experiment during 2009/2010, studied the four potato cultivars used in the glasshouse study, heritage pumpkin (Kamokamo) and modern pumpkin squash (Buttercup squash), in addition to two unnamed oca cultivars grown under rain-fed and full irrigation, in the field (Chapter 4). This was followed by two field experiments in 2010/2011: Irrigation and N management in two Taewa (Moe Moe and Tutaekuri) and Agria, which were compared at three different levels of irrigation and two N rates (Chapter 5). The fourth experiment was undertaken to determine the effect of canopy manipulation on the Taewa cultivar, Tutaekuri (Chapter 6). This chapter provides a general discussion on all the results in order to better the performance of Taewa and other heritage crop cultivars.

7.2 Water requirements for studied heritage and modern crops

Chapters 4 and 5 have shown that modern and heritage crops differ in their growth stages or maturity and also that water distribution with the growing period varies. Growers need to understand the growing stages and related daily water use in order to improve WUE. The daily water use fluctuates within the growing season (Appendix 7.1). The mean daily ET_c for 2009/2010 and 2010/2011, in this study, were 3.2 to 3.6 mm, with a maximum daily ET_c of 6.6 to 7.7 mm in January, and a minimum daily ET_c of 0.3 to 0.4 mm in November, respectively. The daily crop water use for potato was strongly influenced by solar radiation ($P<0.0001$, $r=0.45$) and maximum temperatures ($P<0.0001$, $r=0.52$), but to a lesser amount by wind (Ns, $r=0.12$), according to the correlation analysis with ET_c. The high temperature and solar radiation experienced in January and February (67 - 127 DAP) caused the maximum ET_c (Appendix 7.1). This observation suggests that the water requirement for Taewa is very critical within the months of January and February.

The maximum daily $ET_{c,}$ in this study, is lower than the 12 - 13 mm day^{-1} and higher than the 4 mm day^{-1} reported on potato grown in Portugal (Ferreira *et al.,* 2002) and India (Kashyap *et al.,* 2001), respectively. On the other hand, the $ET_{c,}$ for this study are within the daily potential evapotranspiration range of 0 to 12 mm day^{-1} from winter to summer throughout New Zealand, respectively (NIWA, 2009). Scotter *et al. (2000)* modeled potential evapotranspiration for Palmerston North to have a maximum of 4.2

mm day^{-1} and minimum of 0.7 mm day^{-1} using 25 years of historical weather data whilst Tait *et al.* (2007) estimated the potential evapotranspiration for New Zealand and found rates to range from 0.6 to 4.5 mm day^{-1}. The data for ET_c validate the variability of maximum and minimum potential evapotranspiration between seasons in New Zealand.

Taewa required 610 mm of water over 170 - 180 days, whereas modern potato required 490 - 550 mm for 140 - 150 days. Kamokamo and Buttercup squash required 442 mm over 110 days, whilst oca required 678 mm over 224 days. The irrigation management study (Chapter 5) suggests that rain-fed only provided approximately 60%, and partial irrigation provided approximately 75% of the water requirement for potato. Consequently, rain-fed conditions result in a greater reduction in crop yield than partially irrigated potatoes. Almost all the heritage cultivars studied (Taewa, Kamokamo and oca) use more water than modern cultivars when water is available. Taewa adapts to water stress in time of deficit more than modern cultivars. However, heritage cultivars prioritise allocation of water resources to vegetative growth, compared to modern cultivars (Agria, Moonlight, Buttercup squash) which then optimise partitioning of assimilates to the harvestable products. This observation confirms part of the study hypothesis that heritage crop cultivars differ from modern crop cultivars in their ability to use water.

7.3 Morphological and physiological characteristics of Taewa

7.3.1 Vegetative growth characteristics and dry matter partitioning

One of the most interesting findings is that total dry matter production potential does not differ genetically between Taewa and modern cultivars (Chapters 4 and 5). However, Taewa and the modern potato differ in HI, due to the way in which each cultivar allocates assimilates to tubers. The results in Chapters 4 and 5 consistently show that Taewa plants are genetically broad and tall with a large leaf canopy, whilst the modern potato plants have a large number of shorter, smaller stems with fewer thick leaves. Taewa (especially Tutaekuri) has a high number of small tubers, whilst modern potato has a few but larger tubers per plant (Chapters 4 and 5). Modern potatoes partition more dry matter to tubers (>60%), whilst Taewa only allocates <60% to tubers with the remainder going to shoots and roots.

These findings corroborate the abundant vegetative growth features observed in old wheat (Koç *et al.,* 2003; Siddique *et al.*, 1990a), soyabean (Frederick *et al.*, 1991) and oat (Ziska *et al.,* 2007), compared to their modern cultivars. The significance of this result is that it suggests that development of the Taewa HI is far from its maximum potential value. The HI for modern potatoes may have nearly reached its maximum potential, as reported for many arable crops (Richards *et al.*, 2002). Consequently, there are more opportunities for Taewa to improve its WUE, through the manipulation of vegetative growth traits in its HI, than for modern potatoes.

The results from the three experiments reported in Chapter 3, 4 and 5 reveal that the potato cultivar's morphological characteristics had a considerable influence on its water and N resource use (Manochehr *et al.*, 2009; van Loon, 1981). Taewa increases root dry matter and shoot to root ratio with water stress, as observed in native Andean drought tolerant potato clones (Schafleitner *et al.,* 2007), whilst N increases vegetative growth, depending on the cultivar (Chapters 3 and 5). Manochehr *et al.* (2009) reported that the excess vegetative growth caused by high N does not improve potato tuber yield, as also observed in Taewa. The general view of the effect of water and N reveals that, apart from using more water, Taewa has mechanisms that adapt to partial water and N stress.

Taewa's large canopy is disadvantageous to tuber yield but it helps with weed competition. Furthermore, the large canopy increases relative humidity and shading, which can increase pests and diseases incidences, radiation capture and the lodging of plants (Olanya *et al.,* 2007). This finding thus promotes the idea that a focus on modification of the Taewa leaf canopy should be a priority, in order to improve its productivity. Chapter 6 confirms that canopy modification can create a desirable micro-climate, which can reduce disease incidences and, at the same time increase assimilation to tubers, rather than excess vegetative growth.

7.3.2 Photosynthetic WUE and photosynthesis

The other finding in this study is that Taewa and modern potato vary in gaseous exchange, due to the way in which Ci manipulates stomatal aperture and also as a result of maturity differences. During the 2010/2011 study, both A_n and T were significantly reduced, without affecting photosynthetic WUE with water stress. Stomatal conductance and A_n were positively correlated in all the study years, whilst A_n was negatively correlated to Ci. These observations demonstrate that, apart from stomatal closure, mesophyllic conductance is responsible for photosynthetic capacity variability in Taewa and modern potato. This finding is in agreement with Schapendonk *et al.*

(1989), who investigated how water stress affected A_n in five potato cultivars in the glasshouse. They discovered that there was a genotypic variation in A_n under well watered and limited water conditions. However, the response to water deficit was primarily regulated by stomatal closure and secondly, by the mesophyllic activity three days later. In another study on photosynthesis and productivity between old and modern durum wheat, Koc *et al.* (2003) reported that photosynthesis is largely affected by mesophyllic conductance, rather than stomatal conductance. It can now be confirmed that the integration of stomatal and mesophyllic conductance, which restrains photosynthesis in other C3 plants (Flexas *et al.*, 2002; Ripley *et al.*, 2010), also exists in Taewa and modern potato.

Photosynthetic WUE and photosynthesis (A_n) in potato are substantially affected by leaf age (Vos *et al.,* 1987; Ghosh *et al.,* 2000), genotypes (Tekalign *et al.,* 2005), irrigation (Ahmadi *et al.,* 2010) and N (Ghosh *et al.,* 2000; Olesinski *et al.,* 1989). These influences were observed with a photosynthetic WUE and A_n increase over time (from Day 20 to 50) and then a decrease, regardless of cultivar, irrigation and N. The photosynthetic WUE and A_n change with irrigation, N and crop development, indicating that gaseous exchange is sensitive to water and N stress, and growth stage, in both Taewa and modern potato. Chapters 3 and 4 show that Taewa had an extended and high photosynthetic WUE and A_n, due to delayed tuberisation. Taewa growers are, therefore, advised to avoid water stress during the vegetative and development stage associated with tuber formation, in order to enhance photosynthetic capacity that will result in quality tuber set and development.

Taewa achieved equal or high photosynthetic WUE and A_n on average, compared to modern cultivars, due to a superior performance under both well watered and water deficit conditions (Table 3.3, Table 5.4 and Appendix 4.4.3). The higher A_n and low leaf water potential, under rain-fed, suggest Taewa's tolerance to water stress. The result for leaf water potential in Chapter 5 clearly shows that partial irrigation in Taewa does not cause more water stress, as seen with the modern cultivar, Agria. In addition, Chapter 4 (Section 4.3.1) and Chapter 5 reveal a genotypic variation in root: shoot ratio, which is a mechanism of drought or heat tolerance in potato (Basu & Minhas, 1991), in addition to being an indicator for HI (Siddique *et al.*, 1990b). Tutaekuri and Moe Moe's superior root: shoot ratio under water stress confirms that they had more roots for water uptake, than those in modern potatoes. Siddique *et al.* (1990b) reported high HI and WUE in modern wheat cultivars with low root dry matter and root: shoot ratio. Similary, this study found high HI in modern potato with low root: shoot ratio. These findings show that photosynthetic WUE, A_n leaf water potential and root: shoot ratio are outstanding attributes of Taewa, in relation to water use.

7.3.3 Tuber dry matter and specific gravity

Taewa has been found to have a high solid texture and minimum total sugar content, which are common traits for assessing potato tuber quality (Westermann *et al.*, 1994). The results on DM, SG and total sugars prove that Taewa has an excellent processing quality, compared to modern potatoes as formerly reported by Singh *et al.* (2008) between Taewa and Nadine. The high DM and low total sugar content (Chapter 4, Section 4.3.1) in Taewa contributes to FAO Asia and Pacific region potato research needs, as debated by Pandey, (2008). The high SG and DM observed in Taewa are a more suitable quality for high processing cost recovery, whilst the low sugar concentration is essential for processing colour quality in crisps (Dahlenburg *et al.*, 1990 quoting Burton, 1978 and Smith, 1975).

Belanger *et al.* (2002) and Dahlenburg *et al.* (1990) found that the aforementioned tuber characteristics are substantially influenced by soil moisture, N and cultivars. This study shows the stability of higher DM and SG in Taewa, rather than the modern potato (see Chapters 3 and 5), thus confirming the substantial influence of genotypic variation, rather than the environmental effect. Consequently, Taewa can provide potential genetic resources for improvement in the processing quality of modern potatoes within the Asia and Pacific region. However, selection of Taewa for high tuber quality has a compromise on tuber yield, because tuber yield is negatively linearly related to SG [tuber yield = - 98.8 (SG) +116.6] and DM [tuber yield = - 0.53 (DM %) +26.49 (Appendix 7.7).

Generally, the morphological and physiological characteristics traits, in this study, suggest that high A_n in Taewa are responsible for high vegetative growth, whilst late maturity is responsible for high DM and SG. Unfortunately, Taewa's low efficacy in allocating accumulated dry matter to tubers resulted in low HI, compared to modern potato cultivars, despite it having an equal potential for total dry matter productivity. The photosynthetic WUE and vegetative growth results demonstrates that crop improvement has failed to increase relative growth rate and relative leaf area in modern crops, which are the basis for assimilation (despite increasing HI) as reported by Gifford *et al.* (1981). Consequently, low gaseous exchange is reported in modern potato cultivars, compared to Taewa and other old or wild cultivars (Koç *et al.*, 2003). There are many opportunities to maximise WUE and niche market access, through Taewa, due to its exceptional processing quality attributes, high photosynthetic capacity and expandable HI.

7.4 Tuber yield and yield components for Taewa

The average yields of 52.6 t ha^{-1} for Moe Moe under irrigation, in 2009/2010, demonstrate that it can achieve above the average potato yield range of 45.3 - 50.2 t ha^{-1} in New Zealand (FAO, 2009; McKenzie, 1999), if proper agronomic practices are implemented. This result is also within the average potato tuber yield range of 38 - 55.4 t ha^{-1}, upon which most modern potatoes are accepted for release in New Zealand (Anderson *et al.,* 2004; Genet *et al.,* 1997; Genet *et al.*, 2001). In contrast, Tutaekuri yield potential appears to be lower than the average of Moe Moe and modern potato yields. Consequently, the tuber yield gap between the two Taewa is very wide and difficult to close through agronomic practices because it is dependent on genotypic variation (Appendix 7.2). However, both Taewa tuber yields varied with season and N levels (Appendix 7.2). The main driver of change in the average tuber yields between the experiments was the potato psyllid infestation, as explained below (Section 7.4.3).

Compared with 2009/2010, Taewa production in 2010/2011 decreased, with an average tuber yield of 18.1 t ha^{-1} (18.3 to 17.8 t ha^{-1}) in Moe Moe and 10.9 t ha^{-1} (8.4 to 13.3 t ha^{-1}), in Tutaekuri under irrigation and rain-fed environments, respectively (Appendix 7.3). At NZ$962/tonne, a loss of 10.9 to 18.1 t ha^{-1} in Tutaekuri and Moe Moe means that Taewa growers can potentially loose NZ$10,485 to NZ$17,412 per ha, with a potato psyllid infestation. This result shows that one of the main limitations to tuber yield in Taewa is potato psyllid infestation, apart from the low yield potential amongst other Taewa cultivars. Pest and disease control are essential in Taewa, despite their hardiness and tolerance to some biotic and abiotic stresses, which have been developed through their self-selection (Roskruge *et al.,* 2010). Therefore, Taewa growers are advised to strategise pest and disease management, in order to attain maximum yields and to avoid tuber yield decrease between seasons (see Section 7.4.1).

7.4.1 How can Taewa growers maximise water and tuber yield in a modern production system?

7.4.1.1 Water and N management for improving Taewa yield and yield components

The research found that irrigation, N and cultivar can influence tuber yield and yield components of Taewa, through the use of different mechanisms, as observed in other studies (Ojala *et al.*, 1990). The study suggests that the irrigation and N management commonly employed for a modern potato production system is not at all suitable for all Taewa. Similarly, Taewa cultivars vary in their response to water, but they are similar in their response to N. This finding suggests that low yields in Taewa are partly due to inefficient agronomic practices, apart from genetics. Growers can maximise Taewa tuber yields with proper water and N combinations. When water and N input interactions are properly managed in Taewa, their combined effect will maximise tuber yield and yield components. This study, in addition to Hayward's (2002) study, has shown that high N reduces tuber yield in Taewa, in favour of excessive vegetative growth and photosynthetic WUE. The reason for this is that Taewa's water and nutrient use efficiency relies on its morphological and physiological characteristics.

Moreover, yield, WUE and NUE are also negatively affected by the external factors of pest and disease in fully irrigated Taewa. Pests disrupt water and N interaction from maximising the benefits from properly managed water and N. Taewa growers need to prevent excess N and external constraints on irrigated Taewa, because an incorrect amount of N and water reduces yields and wastes irrigation, in addition to causing environmental pollution (Cooke, 1986). Full irrigation and 80 kg N ha^{-1} or partly less, are recommended for Moe Moe (Chapter 5), whilst Tutaekuri can grow without N (or with minimal N) and partial irrigation.

7.4.1.2 Canopy management for improved yield in Taewa

The poor performance of Tutaekuri in the glasshouse and field compelled a study to examine the consequences of leaf canopy manipulation on tuber yield and WUE, under a limited and unlimited water and N environment (Chapter 6). This study suggests that excessive vegetative growth is responsible for low tuber yields and WUE in Taewa, and that this occurrence can be reversed by the use of mechanical or growth regulator canopy manipulations. This finding confirms the hypothesis that Taewa translocates more assimilates to its above-ground biomass, at the expense of large tubers. In addition, studies by Wang *et al.* (2009a) and Wang *et al.* (2010), also agree that chlorocholine chloride (CCC) proportionally reduces potato plant height and aboveground dry matter, whilst enhancing tuber yield in potato.

Chlorocholine chloride's influence on potato tuberisation has also been reported by Sharma *et al.* (1998). It promotes tuberisation by reducing the level of gibberellins, which are reported to inhibit tuber formation and promote stolon and shoot growth in *Solanum tuberosum ssp. andigena* and *Solanum tuberosum* (Kumar *et al.*, 1974; Sharma *et al.*, 1998). The effectiveness and rate of the CCC depends on the environment and cultural management for the plant being treated. Wang *et al.*, (2010) reported that a CCC concentration of 1.5 – 2.0 gl^{-1} increased mineral nutrition in potato leaves, which contributed to a higher tuber yield.

Mechanical leaf topping is practiced on tobacco, tomato, sweet potato and Brussels sprout, in order to enhance the re-allocation of assimilates to a harvestable product (Hossain *et al.*, 1992; Jones, 1971). The topping of potato, at 30+45 and 30+60 days after planting, increased tuber yield by 67% and 92%, respectively (Hossain *et al.*, 1992). The topping of shoots in volunteer potato plants was reported to have reduced the number of tubers and tuber biomass (Williams *et al.*, 2002). Jones (1971) reported that mechanical topping of Brussels sprout reduced leaf area, thus resulting in a high net assimilation rate and the redistribution of dry matter, which was allocated into sprout production.

In contrast, topping sweet potato fresh vines and leaves resulted in reduced root tuber yield, whilst increasing the yield of fresh vines and leaves (Mulungu *et al.*, 2006). The results from Mulungu *et al.* (2006) and Williams *et al.* (2002) are contradictory, in relation to the effects of topping reported in this study (Chapter 6), in addition to Brussels sprout by Jones (1971) and potato by Hossain *et al.* (1992). The main possible reason for this contradiction is their potatoes were topped to ground level. However, the number of positive results (on the effects of canopy topping) outweighs the negative results. This study, therefore, suggests that Taewa growers (in order to maximise their yield and WUE) spray with CCC at Day 25 and 50 for irrigated conditions, whilst spray with CCC at Day 25 and 30 and mechanical topping techniques at Day 52 would suit both irrigated and rain-fed conditions.

7.4.1.3 Controlling the impact of potato psyllid on Taewa yield

Potato psyllid has been causing yield losses to various solanaceous crops (potato, tomato) in New Zealand since 2006 (Teulon *et al.*, 2009; Puketapu, 2010). In this study, potato psyllid did not affect the 2009/2010 Taewa and modern potato crop, following the spraying of 600g/litre methamidophos (Metafort 60SL), an organo-phosphorus insecticide. However, a potato psyllid infestation was observed late (150 DAP) in the 2010/2011 season, following the spraying of Avid (abamectin) and Confidor (imidacloprid), as presented in appendix 7.3. The results for 2010/2011 indicate that there was a great reduction in tuber yield and tuber quality (SG and DM) in Taewa potato, compared to 2009/2010, as also reported in modern potato by Teulon *et al*. 2009.

The yield loss in Taewa (especially Moe Moe) was higher (>40%) than that in the modern potato cultivar, Agria (13%). New Zealand’s national potato psyllid monitoring results indicate that the potato psyllid population in the Manawatu region was not serious in 2009/2010, compared to 2010/2011 (Fig 7.1). It also indicates that the potato psyllid population was high (in this experiment) 150 days (14 - 28th March) after planting in 2010/2011. This trend of potato psyllid outbreak suggests that the difference in potato psyllid impact between years is not due to the effectiveness of insecticides used, but instead it is due to the size of the potato psyllid population and the time of the outbreak. Agria, might have escaped the potato psyllid ordeal, due to its early tuberisation and maturity.

The spraying of pesticides in 2010/2011 (Appendix 7.3) did stop at the time the modern potato had reached physiological maturity, and this was the same time that the potato psyllid population in Manawatu peaked (Fig. 7.1). Potato psyllid disrupted dry matter accumulation, at the critical stage of Taewa’s tuber dry matter accumulation (Plate 5.3). Hence, Taewa required extended spraying, in order to avoid the impact of potato psyllid at the later stage. The extension of a potato psyllid protection programme has an economic implication on Taewa growers, because it suggests an extended crop protection period to 170 days. Taewa will need more labour and chemicals costs, than for modern potato, in the case of potato psyllid protection. Taewa may require 15 - 17 sprays at 10 days interval, whilst modern potato may only require only 8 - 10 sprays (Appendix 7.3).

The observations on potato psyllid infestation in 2010/2011 (and viral disease in the glasshouse experiment on Taewa) confirm part of the study hypothesis that Taewa yields fell short, primarily due to agronomic practices (pest and disease infection) disparity, rather than susceptibility to pest and diseases conditioned genetics. Taewa growers need to take pest and disease control seriously, in order to attain high tuber yield, quality and tuber dry matter content.

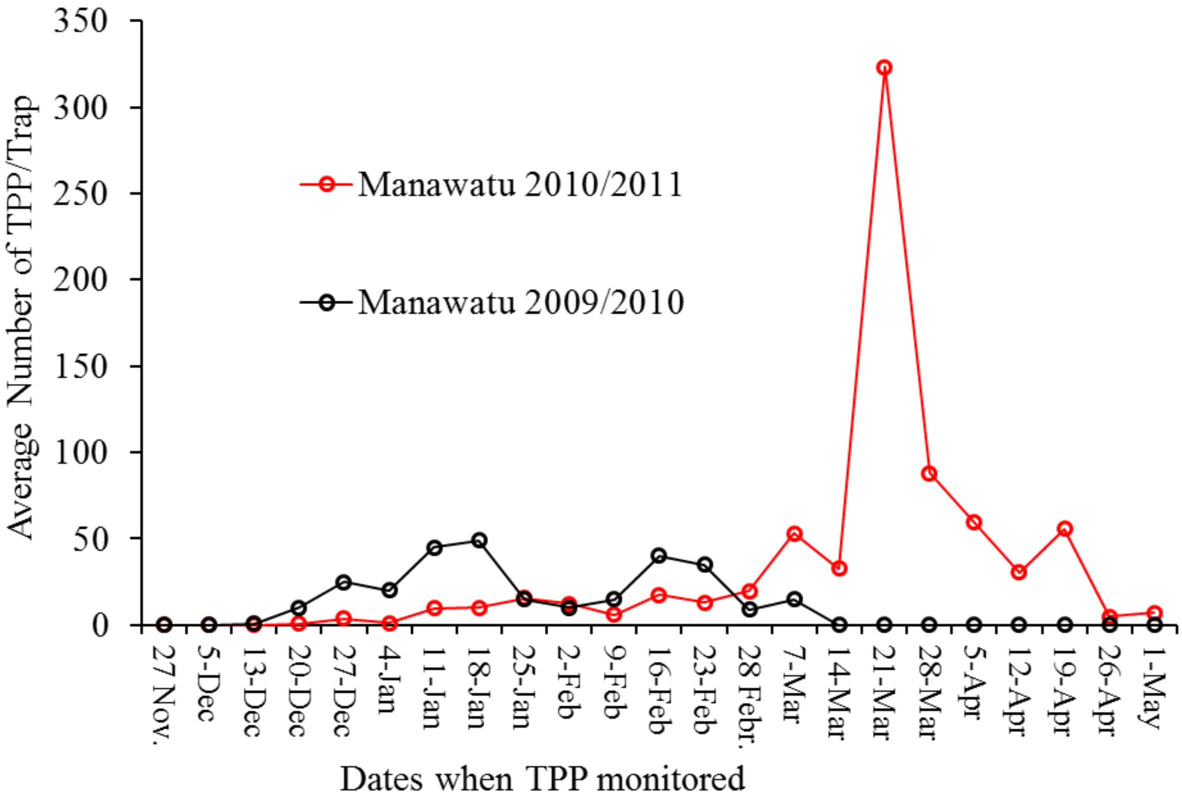


Figure 7.1 Average numbers of potato psyllids (PP), per trap monitored in Manawatu region, during the 2009/2010 and 2010/2011 growing season (Sourced from http://www.potatoesnz.co.nz/Overview/What-we-are-working-on/Psyllid-resources.htm), Potato New Zealand.

7.5 Key water use performance indicators

Water use efficiency is one of the main indices for water use in New Zealand (Aqualinc, 2006; Ford *et al.*, 2009). This study has assessed the performance of heritage and modern crop cultivars, in addition to agronomic practices, using a drought sensitivity index (DII); yield reduction percentage (PR%); geometric yield mean (GM_y) (Ramirez-Valejo *et al.*, 1998); crop water use efficiency (WUE) (Howell, 2001); water footprint (WF) or virtual water content (VWC) (Hoekstra *et al.*, 2009); economic water productivity (EWP) (Barker *et al.,* 2003; Molden *et al.,* 2001); nitrogen use efficiency (NUE) (Zebarth *et al.,* 2008 and irrigation water use efficiency (IWUE) (Howell, 2001).

The DII, GM and PR% investigated the cultivars' genotypic sensitivity to water or drought situations; crop water productivity and WF; EWP investigated the physical and economic productivity of cultivars, at a given unit of water; and IWUE investigated the marginal increase in yield, per unit of irrigation, in heritage and modern cultivars. The water footprint was used to compare cultivars between crops, whilst specific WUE was used to compare cultivars within one crop. Several indices were used so as to quantify the physical and economic effects of changing varieties, irrigation and N management. Marsh *et al.,* (1998) recommended the use of several indicators because they offer a more accurate result, per factor.

This study found that water use performance indicators for the heritage and modern potato, pumpkin squash and oca fit in three categories: 1) one set indicated more yield, per unit of water used; 2) one set indicated a high marginal yield return, per additional unit of irrigation; and 3) one set indicated a higher economic return per unit of water used. Pumpkin squash (especially, Kamokamo) had more yield, per unit of water used because of its highest yield potential and EWP. Moe Moe has the highest EWP among potatoes, mostly due to its greater market value. On the other hand, modern potatoes responds well to irrigation, compared to pumpkin squash and Tutaekuri, due to their high IWUE and sensitivity to water stress. The selection of a crop for limited water should be based on its high yield and low yield reduction with water stress, in addition to EWP and low water footprint (as noticed in Kamokamo and Moe Moe). The selection of a crop for irrigation optimisation should be based on high IWUE, as well as high EWP and high yield potential (as observed in Agria and Moonlight).

The heritage crops studied are relatively insensitive to soil moisture stress, compared to modern crops (especially modern potato). For instance, the results in Chapter 4 demonstrate that some heritage cultivars do not need full irrigation, even when water is limited, due to their genetic makeup (as observed in Tutaekuri), whilst others need irrigation, due to their late maturity (as observed in oca). The water stress indicators mentioned in Chapter 4 and 5 support the morphological and physiological characteristics in heritage crops, which can withstand water deficits, compared to modern potatoes. Nevertheless, irrigation is essential for quality improvement in heritage crops. Where water is scarcer in New Zealand, partial irrigation may be an option, in this case, irrigation could be applied during sensitive crop development stages, rather than using a scarce water resource over oca or Taewa's entire and extended growing season. These results suggest that key WUE indicators can easily be applied in selecting heritage crop enterprises or shifting to profitable heritage crop enterprises basing on a combination of market premiums, physical water productivity and water availability.

7.5.1 Water footprint of growing potato, oca and pumpkin squash

The mean total water footprint for full irrigation and rain-fed ranged from 95 to 111 m^3 $tonne^{-1}$ (modern potato); 110 - 220 m^3 $tonne^{-1}$ (Taewa); 46 - 82 m^3 $tonne^{-1}$ (pumpkin squash) and 261 - 335 m^3 $tonne^{-1}$ (oca) in 2009/2010 (Chapter 4). In 2010/2011 the mean water footprint for water regimes ranged from 163 - 586 m^3 $tonne^{-1}$ (FI), 173 - 406 m^3 $tonne^{-1}$ (PI) and 198 - 505 m^3 $tonne^{-1}$ (rain-fed), with the lowest being found in Agria and the highest in Tutaekuri (Appendix 7.4). The water footprint of Taewa greatly increased in 2011, compared to 2010, due to a potato psyllid infestation and differences in maturity. It was found that the water footprint was reduced by partial irrigation for Tutaekuri and by full irrigation for Moe Moe and Agria. In New Zealand, Hedley (2009a) has reported that the water footprint of modern potato production is smaller than the water footprint of maize and pasture: with potato registering 308 m^3 $tonne^{-1}$ and 325 m^3 $tonne^{-1}$; maize registering 622 m^3 $tonne^{-1}$ and 654 m^3 $tonne^{-1}$; and pasture registering 2651 m^3 $tonne^{-1}$ and 2667 m^3 $tonne^{-1}$, at varied rate irrigation and uniform rate irrigation, respectively.

The total water footprint of growing potato, in the study by Hedley *et al.* (2009ab), was higher than those reported by Hoekstra (2003) and the water footprint for this study, except for Tutaekuri. The water footprint of growing potato with no psyllid infestation (in both Taewa and modern potato), in 2009/2010 (Chapter 4), is lower than the global water footprint (160 m^3 $tonne^{-1}$) of growing potato. In the case of potato with psyllid infestation in 2010/2011, only a well managed full irrigation regime of modern potato and Moe Moe, gave a water footprint approximating the global water footprint of 160 m^3 $tonne^{-1}$. Partial irrigation improved the water footprint of Tutaekuri. Partial irrigation reduced the water footprint, by lowering the water volume needed to produce potato per tonnage by 12.6%, whilst maximising tuber yield over that found in the rain-fed crops.

The water footprint indicator suggests there are numerous disparities, with global averages and within country or seasons, arising from irrigation management and methodological differences when estimating crop water use, climate variability, cultivars and pest and disease infestation (Kumar *et al.* 2007; Hoekstra *et al.,* 2007). However, the water footprint for crops grown in New Zealand can be reduced through good management (Mekonnen *et al.*, 2010b). For instance, pumpkin squash (especially Kamokamo) had the lowest water footprint, compared to oca, potato, maize and pasture in New Zealand, and compared well with small water footprint crops such as sugar beet and sugarcane, at the global level (Gerbens-Leenesa *et al.,* 2009a). This observation suggests that some heritage crop cultivars can compare with (or outperform) modern cultivars in relation to water footprint, when the crop husbandry is appropriate.

7.5.2 Water use efficiency and crop water production functions in Taewa

7.5.2.1 Water use efficiency benchmarks in Taewa

This study found WUE in potato ranging from 3.3 to 12.4 kg m^{-3} amongst cultivars and 5.8 to 11.2 kg m^{-3} amongst water regimes (Chapter 4 & 5). Tuber yield and NUE declined with PI and rain-fed, whilst it enhanced WUE, compared to FI in Agria and Moe Moe. This corroborates the findings of Martin *et al.* (2006) who reported that high WUE in pasture production (rye grass and white clover) in New Zealand are obtained with restricted irrigation; but this is at the cost of pasture production. Water use efficiency for potato is higher than the WUE of pasture which is benchmarked at 2.0 kg DM $ha^{-1}m^{-3}$ with a range from 0.07 to 2.1 kg DM $ha^{-1}m^{-3}$ in New Zealand (Martin et al., 2006). In this study, Taewa and modern potato optimal WUE is benchmarked at 6.5 kg m^{-3} for modern potato, 6.0 kg m^{-3} for Moe Moe and 3.7 kg m^{-3} for Tutaekuri, using the method of Martin *et al.* (2006) for benchmarking pasture production WUE (Appendix. 7.5).

Amongst the world's major food crops, potato has been reported to have a high WUE of 6.2 - 11.6 kg m^{-3}, compared to cereal and legume grain crops (Bowen, 2003; FAO, 2008; Thompson *et al.,* 2003; Zhang *et al.,* 2005). The WUE for modern potato and Moe Moe are within this range. Water use efficiency for potato has been reported above 11.6 kg m^{-3}, as also observed with some modern potato treatments in this study (Kang *et al.,* 2004; Trebejo *et al.,* 1990). Erdem *et al.* (2006) reported WUE for potatoes below 6.2 kg m^{-3}, as observed in Tutaekuri. The reason for low WUE in Tutaekuri could be its genetics on small tuber size or higher tuber number and higher vegetative growth than tuber yield. The WUE for Tutaekuri improved with the enhancement of HI as reported in grain WUE (Siddique *et al.*, 1990a). The WUE for Tutaekuri is above WUE for the major crops of the world and therefore, may be a valuable crop when water is limited.

7.5.2.2 Irrigation water use efficiency and water stress index in Taewa

Irrigation needs to be well planned for tuber yield and water resources optimisation in Taewa and modern potato cultivars. This study indicates that partial irrigation is optimal for Tutaekuri, whereas full irrigation is optimal for Moe Moe and Agria, because that is where the IWUE and yield were maximised. A failure to decide on these irrigation schedules can lead to a risk of yield reduction by 28.1% in Tutaekuri and 34.1% and 32.9% in Moe Moe and Agria, respectively (Table 5.9). The IWUE results, in combination with high yield reduction and high GM in Agria, highlights that the modern cultivar is physiologically more able to transform water to tuber (when water is optimal), compared to Taewa with its tolerance to water stress. Taewa exhibited high drought tolerance characteristics under water and N stress. This ability confirms the findings from the physiological characteristics that suggest heritage crops are well adapted to low water and N supply, despite their low yield potential.

Novel irrigation technologies enhance WUE by reducing non-stomatal water loss whilst efficient water use crops enhance WUE by increasing ET-Yield slope. In New Zealand, Hedley *et al.* (2009b) evaluated the IWUE of variable rate irrigation (VRI), compared to uniform rate irrigation (URI), on a range of soils at five sites using centre pivot irrigator on pasture, maize and potatoes. It was found that VRI enhanced IWUE at all sites with the highest IWUE being found in potato (5.6 vs 6.8 kg m^{-3}), whereas maize (3.3 vs 3.7 kg m^{-3}) and pasture (3.3 vs 4.6 kg m^{-3}) were low (Hedley *et al.*, 2009b). Onder *et al.* (2005) investigated the IWUE of surface drip and sub-surface drip irrigation at full irrigation (FI), 66% of FI and 33% of FI and non-irrigated, where they found that IWUE was enhanced by deficit irrigation and surface drip irrigation (9.3 to 25.4 kg m^{-3}), whilst full irrigation and subsurface irrigation had the lowest IWUE (9.0 to 23.0 kg m^{-3}).

In another study, Erdem *et al.* (2006) reported that IWUE values increased from furrow (5.8 to 8.6 kg m^{-3}) to drip irrigation (7.2 to 13.7 kg m^{-3}) (Erdem *et al.*, 2006). Some IWUE results in this study are greater than those found in reports by Hedley *et al.* (2009b) and those cited previously, except from drip irrigation. The main cause for the variation appears to be the cultivar, in addition to irrigation management effects. The effect of cultivar on IWUE is greater than the effect of irrigation scheduling. Therefore, Taewa growers are recommended to combine techniques that maximise both consumptive water use and reduce run-off, in order to achieve high WUE (English *et al.,* 2003).

7.5.2.3 Economic water productivity benchmarks in Taewa

The concept for WUE needs to focus on achieving more cash per unit of water used, apart from sustaining the environment and gaining more fruit yield per volume of water used, in order to sustain profitability in cases of high water cost and water scarcity (Aldaya *et al.,* 2008). The economic water productivity in this study reports high EWP under partially irrigated treatments. The EWP ranged from 13.2 to 33.5 NZ$ m^{-3} for cultivars and 20.7 to 23.2 NZ$ m^{-3} for water regimes in 2010. In 2011, EWP ranged from 13.0 to 19.3 NZ$ m^{-3} for cultivars and 14.6 to 17.0 NZ$ m^{-3} for water regimes. The decline in average EWP for both cultivars and water regimes in 2010/2011 indicates the negative economic implication of potato psyllid infestation and weather on EWP. This finding on EWP suggests that WUE in potato is a product of different factors: optimal irrigation scheduling, pest and disease and cultivars and market price.

Agria and Moonlight have high physical WUE, but they are not as economically productive under the same volume of water as Moe Moe. Similarly, the irrigation scheduling technology, for improving water use in Agria, is different for Tutaekuri. The results on EWP confirm the findings of Nielsen *et al.* (2005) that WUE, based on a dollar return per unit of water used, is sometimes high in those crops found with low evaporative demand (chickpea and canola), rather than those crops with a high evaporative demand (cereals) (Nielsen *et al.,* 2005; Nielsen *et al.,* 2006). Likewise, market values or high values have determinature effect on EWP. Aldaya *et al.* (2008) reported that the use of water for low value crops is sometimes the main problem, rather than water scarcity. Vegetables with high value were more economically productive, per volume of water (15 Euro/m^3 ≈ 27 NZ$/$m^3$), than grain cereal with less value (0.3 Euro/m^3 in Spain (Aldaya *et al.,* 2008). In this study, heritage cultivars (Moe Moe, Kamo Kamo) demonstrated higher cash per volume of water used than modern cultivars with their high yield per unit of water. These results, together with those reported from other authors; suggest that the market value of a product should be one of the driving forces in the allocation of water, in New Zealand.

7.5.3 Nitrogen use efficiency benchmarks in Taewa

Nitrogen use efficiency is found to be highest under unlimited irrigation and limited N, but the consequence is that WUE is reduced (Chapters 3 and 5). On the other hand, NUE was found to greatly differ between modern potato and Taewa. Zebarth *et al.* (2008) found that commercial potato cultivars have a higher or equal NUE, compared to Andean primitive cultivars; this finding is similar to this study. However, this study does not agree with Zerbarth's earlier study (Zebarth *et al.*, 2004), which indicated that late maturity increases NUE: Taewa, although late maturing, has a low NUE compared to the short duration cultivar, Agria (Zebarth *et al.,* 2004).

In another similar study, Errebhi *et al.* (1999) assessed NUE in tuber bearing solanum species (wild species and their hybrids) and commercial cultivars, at low and high N. It was found that NUE was highest in wild species, with a minimal difference from Russet Burbank, but it was greater than that found in other modern potato cultivars (Errebhi *et al.,* 1999). Taewa, especially Tutaekuri, has low NUE and WUE, due to their self-selection for survival to adverse competition and environmental factors, whilst modern or commercial potato cultivars are either bred for high NUE or WUE (Zebarth *et al.*, 2008). However, the comparison of Taewa NUE with wild species (Errebhi *et al.*, 1999) suggest that NUE also varies between unimproved potato species (heritage or wild specises) with others exhibiting high NUE whilst others low NUE.

An increase of application N from 80 to 240 kgN ha^{-1}, has a marginal average yield increase of 23.8Kg kgN^{-1} in modern potato, Agria whilst Taewa has a marginal average yield decrease of 9 kg kgN^{-1} in Moe Moe and a marginal yield decrease of 53.4 kg kgN^{-1} in Tutaekuri (Appendix 7.6abcd). This suggests that there are no marginal benefits in the Taewa yield with N being above 80 kg N ha^{-1}, since Taewa is not bred for high N (Appendix 7.6). Taewa may be appropriate over modern potatoes when N resources are limited. Appendix 7.7 presents marginal productivity stratified by N and water regime, in order to measure marginal change in NUE, as one water regime is replaced by another. Marginal productivity is a satisfactory guide for farmers to make a balanced decision on how much N they should use with a particular water regime (Cooke, 1986). In regards to this study, it is not rational for Taewa growers to operate above 80 kg N ha^{-1} with all water regimes, but modern potato can be produced at above 80 kg N ha^{-1} with FI and PI (Appendix 7.6). Maori people may select Taewa, due to its low N requirement, which easily meet their input investments, within their limited resources.

7.6 Comparison of Tutaekuri and Moe Moe Characteristics

Tutaekuri is *Solanum tuberosum subsp. andigena*, whilst Moe Moe is *Solanum tuberosum subsp. tuberosum* (Harris, 2001). Throughout this study, Tutaekuri exhibited fewer and larger stems with more branches, in addition to many small tubers and a higher shoot: root ratio, compared to Moe Moe. However, Chapters 4 and 5 indicate that Moe Moe and Tutaekuri have similar height and number of stems. Occasionally, Moe Moe exhibited more tubers than Tutaekuri. On the other hand, the tuber yield, HI, WUE and NUE for Tutaekuri was lower than that for Moe Moe. Moe Moe managed to achieve high tuber yield and HI by modifying its tuber numbers with irrigation, which is different to Tutaekuri.

Tutaekuri allocated more to stolons and roots. Harris (2001) also observed that Tutaekuri has long stolons. Tutaekuri responded to partial irrigation whilst Moe Moe performed well under full irrigation. Both Tutaekuri and Moe Moe required very low N. Despite some similarities, it can be concluded that specie’s variations are high within Taewa except that both cultivars were not bred specifically for high water and N use and both can provide a profitable business for Maori people, with the highest expectation for Moe Moe.

7.7 Economics of irrigation on Taewa

Economic assessment of Taewa in relation to irrigation investments using the Net Present Value method (NPV) is presented in Appendix 7.8. The economic results indicated that Moe Moe, had the highest additional gross revenue on investment income; additional annual revenue per ha from irrigation in the 1st year; net present value (Appendix 7.8.3; Appendix 7.8.4) and shortest repayment period, due to its high value and intermediate marginal yield increase with full irrigation and low N. Modern potato, Agria, was the least economic crop enterprise in relation to gross revenue on investment income; present value or additional annual revenue per ha from irrigation in the 1st year; net present value and longer repayment period, due to its low market value compared to Taewa.

Tutaekuri had an intermediate gross revenue on investment income; present value or additional annual revenue per ha from irrigation in 1st year; net present value; and intermediate repayment period, despite a low marginal yield with irrigation, due to its premium prices, partial moisture requirement and low N use. Moreover, the gross revenue for Tutaekuri is expandable by 38% with canopy management. This result suggests that fully irrigated Moe Moe and partially irrigated Tutaekuri, with low N, would be profitable investments for Taewa growers; due to their high value and low N use. Growers are not advised to produce Tutaekuri under full irrigation and high N, in addition to Agria under partial irrigation and low N, because these production systems have negative NPV after an initial investment of NZ$6557/ha (Appendix 7.8.3; 7.8.4). Taewa, a traditional crop, can be produced economically, whilst supporting water conservation and low N input to the environment in New Zealand.

7.8 Practical implications of the study for Taewa growers

This study may contribute to Primary Industry policy on sustainable economic growth and improved economic, social and cultural benefits from the environment (MAFF, 2011). The study may also contribute to the resource efficiency policy of the Ministry of Environment in New Zealand on achieving environmental standards, whilst sustaining and improving social and economic development (Miskell, 2009). The study may provide sustainability indicators for improving Taewa growers' prosperity in crop production and environmental management. It may also present part of New Zealand's solution to economic water scarcity, which is expected to increase, by 2025 (IWMI, 2000, 2002). Small scale growers may also improve marginal returns, by reducing irrigation and N costs and improving yields through selection of genotypes with high WUE or tolerance to water stress, suggested in this study.

Research on heritage crops contributes to the New Zealand Government's policy on improving Maori land use and sustainable development (MAFF, 2011). Provision of innovative technology to Maori on natural resources management increases their authority, possession and protection outlined in Waitangi Treaty between Maori and the British Crown on 6th February, 1840 (Latiner, 2011). This study achieves part of this policy by supporting the livelihoods of Taewa growers and society though cultural economy which is rarely considered (Miskell, 2009). It also delivers scientific information to protect and improve resources of cultural value to Maori community

(MAFF, 2011). Irrigation and canopy management study on Taewa can be one of the novel strategies for increasing Taewa products in the "new economic space" and "cultural resilience" among Taewa growers (Lambert, 2008). Taking on board the recommendations of this study is one way the New Zealand Government may ensure the biodiversity of New Zealand's species and win-over Taewa growers to efficient resource use, through heritage crops.

7.9 Conclusion and suggestions for future research

The morphological and physiological characteristics of Taewa include higher vegetative growth; higher photosynthetic WUE; lower leaf water potential; higher tuber dry matter content; and higher specific gravity than modern potatoes. Modern potatoes excelled in area of early tuberisation, tuber yield and HI. This study also shows that irrigation and N are paramount for enhancing photosynthetic WUE; photosynthetic capacity; and tuber yield — regardless of canopy manipulation. Nitrogen application is not always advantageous for Taewa. Canopy manipulation failed to enhance tuber yield, when high N was applied to Tutaekuri**.**

It can be concluded that modern potatoes are more responsive to irrigation and N application than Taewa. Taewa use more water (when available), due to late maturity, and are also tolerant to water stress in time of scarcity, unlike modern potatoes. As a result, irrigation and N are important for both Taewa and the modern potato cultivars — although in different ways. Modern cultivars had higher WUE and NUE, than heritage cultivars. However, some heritage cultivars (Moe Moe and Kamokamo) have comparable yield and WUE capability to modern cultivars. The heritage cultivars' WUE is high when assessed in economic terms. The increased vegetative growth, the higher number of tubers and the disparity in appropriate agronomic practices (pest and disease control) contribute to the low yield and physical WUE commonly observed in heritage crops. Partial irrigation and low N combinations are recommended for Tutaekuri, whilst Moe Moe requires full irrigation, similar to modern potato, but with low N in contrast to modern potato.

Management of the canopy increased the total yield and marketable tuber yield by 26% (20 - 33%) and 38% (32 - 44%) in Taewa cultivar, Tutaekuri. This resulted from the redistribution of dry matter from excessive vegetative growth to the tuber. However, the final tuber yield depended on how canopy management prepared the plant to use water efficiently. Applying CCC at Day 25 and 30 DAE and canopy topping easily partitioned more assimilates to the roots, whilst applying CCC at Day 25 and 50 DAE delayed root development potentially making the crop very sensitive to water stress. For this reason, application of CCC at Day 25 and 50 DAE would be suggested for irrigated conditions, whilst the remainder would suit both irrigated and rain-fed conditions. Taewa growers should apply mechanic and hormonal canopy manipulation, irrigation and pest and disease control strategies stipulated in this study in order to optimise water use and tuber productivity.

The economic analysis of growing Taewa has also indicated that Taewa can be produced economically under small scale irrigation, with partial irrigation and low N input. Taewa is potentially a profitable business with proper water, N and canopy management as determined in this study. In this case, it can be concluded that most heritage crops have potential economic WUE based on premium market values whereas modern crops have potential physical WUE based on high yield. Hence, heritage crops can provide alternative land use to sustain water and N use whilst improving productivity and economic gains among small scale growers of New Zealand. It is apparent in this study that selection of Tutaekuri for improved HI is a good criterion for enhancing Taewa yield and WUE.

7.9.1 Future Research

Most detailed research on Taewa has been primarily social in nature, except the studies by Roskruge (1999), Hayward (2002) and Harris (2001). This thesis on Taewa and those aforementioned studies all highlight the need for further research in various agronomic areas, in order to promote and meet the demands for Taewa within various potential niche markets. Then if warranted, there is a need to consider Taewa response to a wide range of water and N treatments and to study how Taewa responds to N increase from zero, in order to determine optimal production levels. Field or glasshouse investigations on why Taewa genotypes have better yields under low N than high N fertilisation, compared to modern potatoes would be interesting. A molecular study would help to identify genes for improving NUE in modern potato or to determine how Taewa NUE and WUE traits control growth and biomass production, in a different way from modern potato.

There is need to examine phenotyping for drought tolerance in Taewa genotypes, since they have exhibited a level of tolerance to water and N stress. However, this study did not observe the cultivars' degree of tolerance to chronic and transient drought, or heat tolerance. This study has also demonstrated that drought increases root dry matter in Taewa, but root length and diameter were not investigated. A thorough investigation is needed on root architecture imaging, and root expression mapping could help to identify desirable root traits for the development of cultivars with desirable root: shoot ratio and HI, which favour both tuber yield and biomass production from Taewa. These investigations would help breeders to determine surrogate traits that are related to low N soils or drought tolerance in Taewa.

For organic farming purposes, research is required on how Taewa responds to farmyard manure, compost and biosolids, or integrated organic-inorganic fertiliser management, under varied water regimes. There is also a need to develop a crop simulation model specifically for Taewa, in order to help growers predict growth, development and productivity of Taewa, at different N and water environments. A potato calculator (Jamieson *et al.* 2004), which is used by a number of growers and researchers, does not fit many of Taewa's physiological and morphological characteristics. Finally, there is a need to further assess the appropriate time for topping Tutaekuri (*Solanum andegina)* and other Taewa cultivars.

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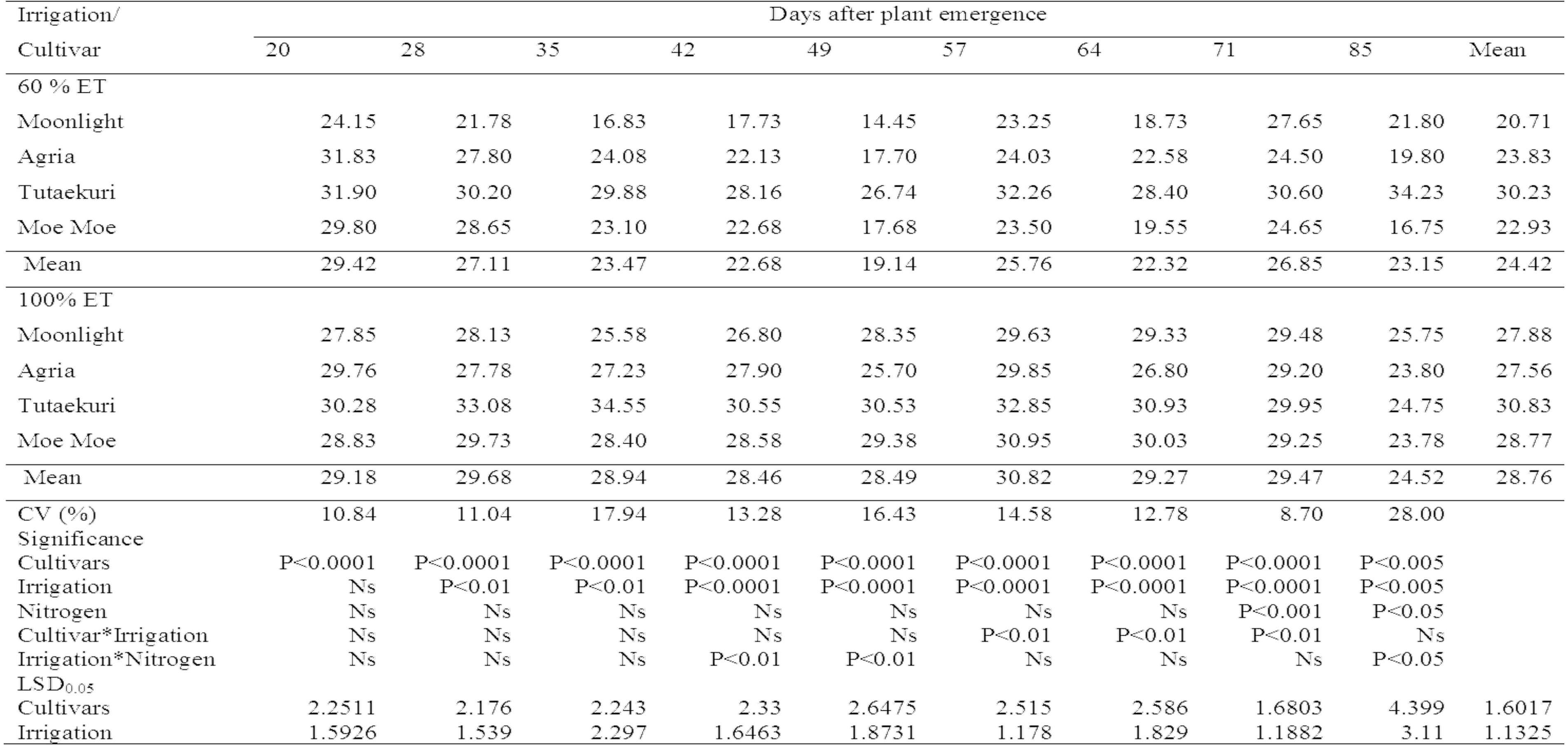
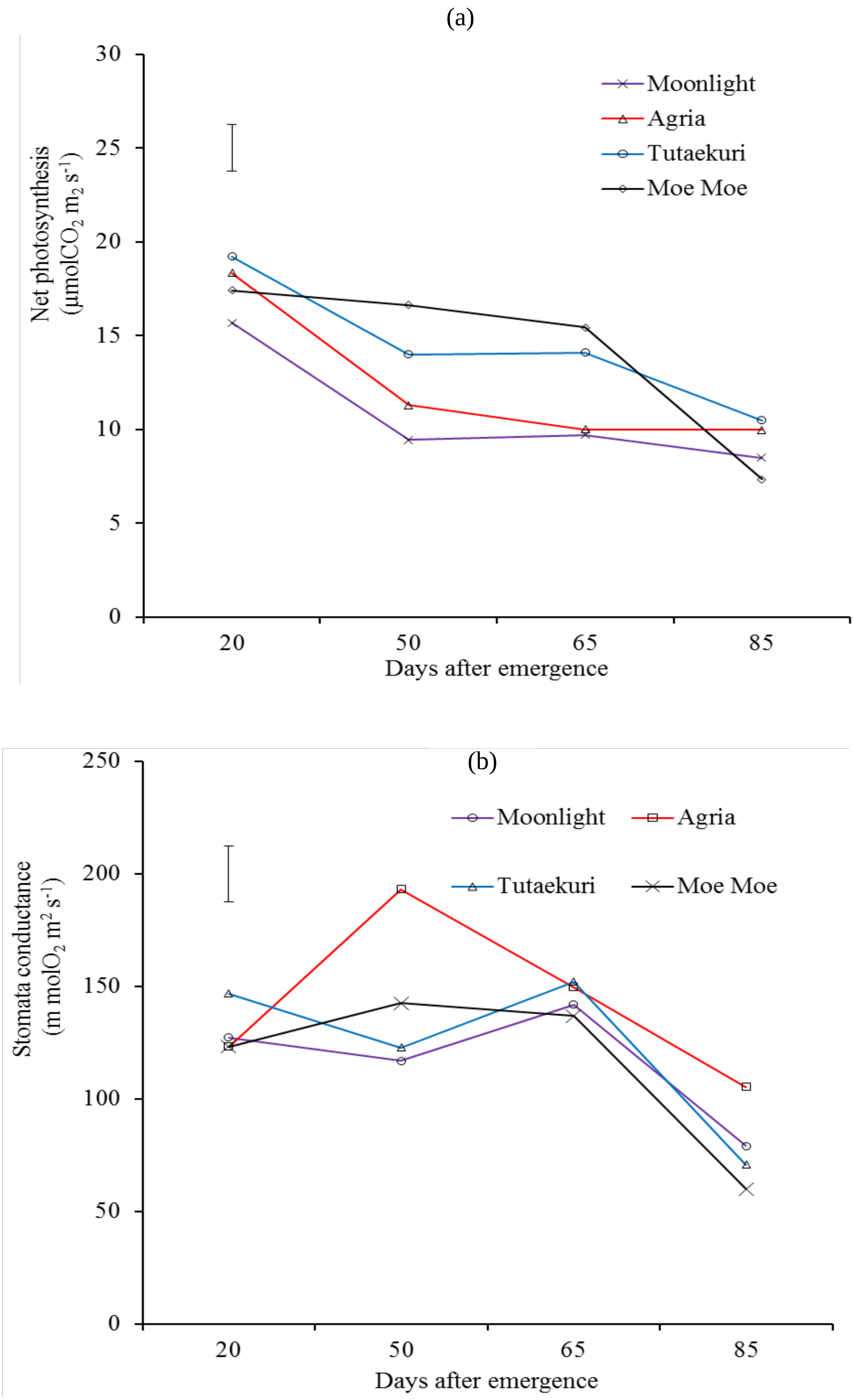
APPENDICES

Appendix 3.1 Effect of water regime, nitrogen and cultivars on volumetric soil moisture content (%) in the glasshouse, 2009

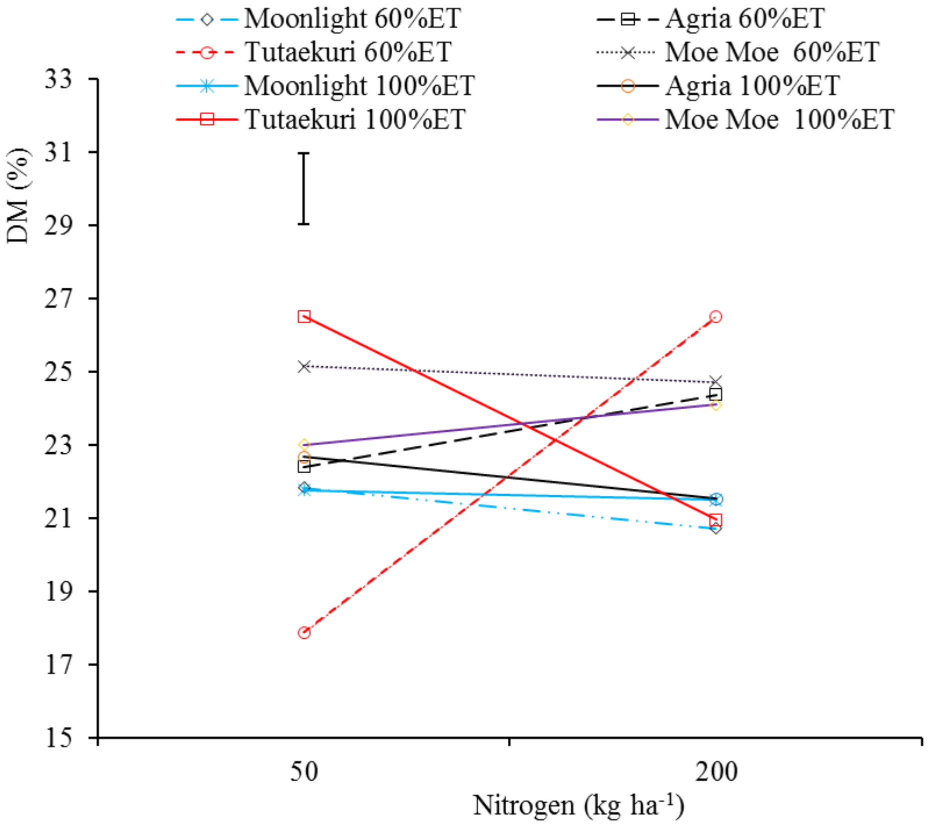


Irrigation/	Days after plant emergence									
Cultivar	20	28	35	42	49	57	64	71	85	Mean
60 % ET										
Moonlight	24.15	21.78	16.83	17.73	14.45	23.25	18.73	27.65	21.80	20.71
Agria	31.83	27.80	24.08	22.13	17.70	24.03	22.58	24.50	19.80	23.83
Tutaekuri	31.90	30.20	29.88	28.16	26.74	32.26	28.40	30.60	34.23	30.23
Moe Moe	29.80	28.65	23.10	22.68	17.68	23.50	19.55	24.65	16.75	22.93
Mean	29.42	27.11	23.47	22.68	19.14	25.76	22.32	26.85	23.15	24.42
100% ET										
Moonlight	27.85	28.13	25.58	26.80	28.35	29.63	29.33	29.48	25.75	27.88
Agria	29.76	27.78	27.23	27.90	25.70	29.85	26.80	29.20	23.80	27.56
Tutaekuri	30.28	33.08	34.55	30.55	30.53	32.85	30.93	29.95	24.75	30.83
Moe Moe	28.83	29.73	28.40	28.58	29.38	30.95	30.03	29.25	23.78	28.77
Mean	29.18	29.68	28.94	28.46	28.49	30.82	29.27	29.47	24.52	28.76
CV (%)	10.84	11.04	17.94	13.28	16.43	14.58	12.78	8.70	28.00	
Significance										
Cultivars	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.005	
Irrigation	Ns	P<0.01	P<0.01	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.0001	P<0.005	
Nitrogen	Ns	Ns	Ns	Ns	Ns	Ns	Ns	P<0.001	P<0.05	
Cultivar*Irrigation	Ns	Ns	Ns	Ns	Ns	P<0.01	P<0.01	P<0.01	Ns	
Irrigation*Nitrogen	Ns	Ns	Ns	P<0.01	P<0.01	Ns	Ns	Ns	P<0.05	
$LSD_{0.05}$										
Cultivars	2.2511	2.176	2.243	2.33	2.6475	2.515	2.586	1.6803	4.399	1.6017
Irrigation	1.5926	1.539	2.297	1.6463	1.8731	1.178	1.829	1.1882	3.11	1.1325

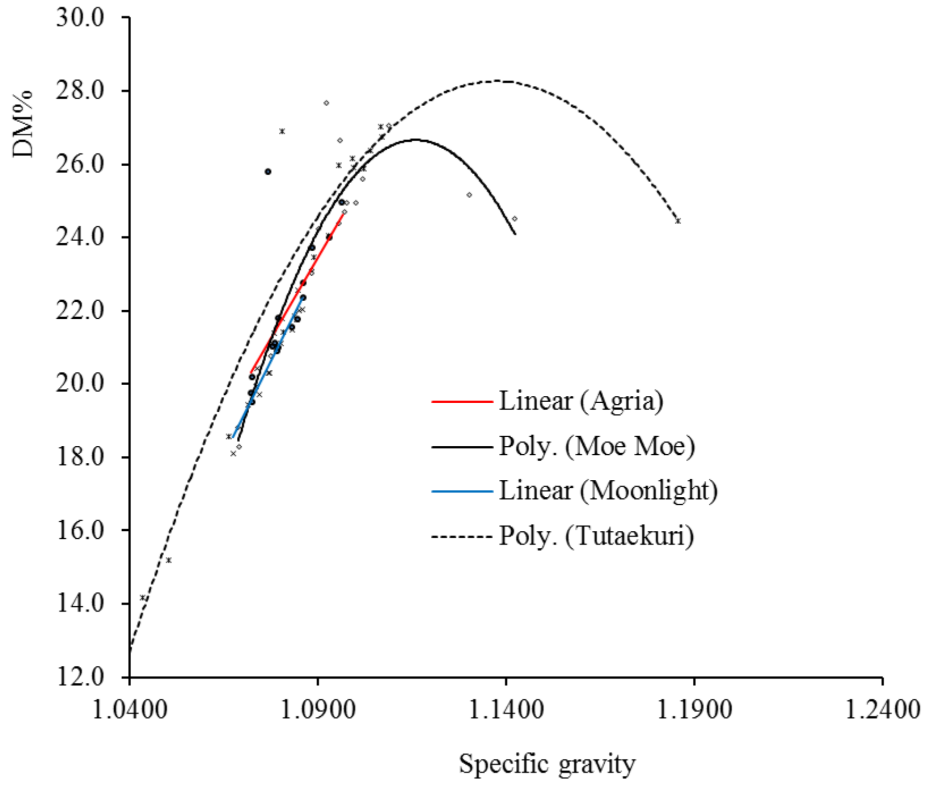
Appendix 3.2 Change of A_n and g_s in potatoes during the growing season in the glasshouse 2009; Error bars represent ±SEM



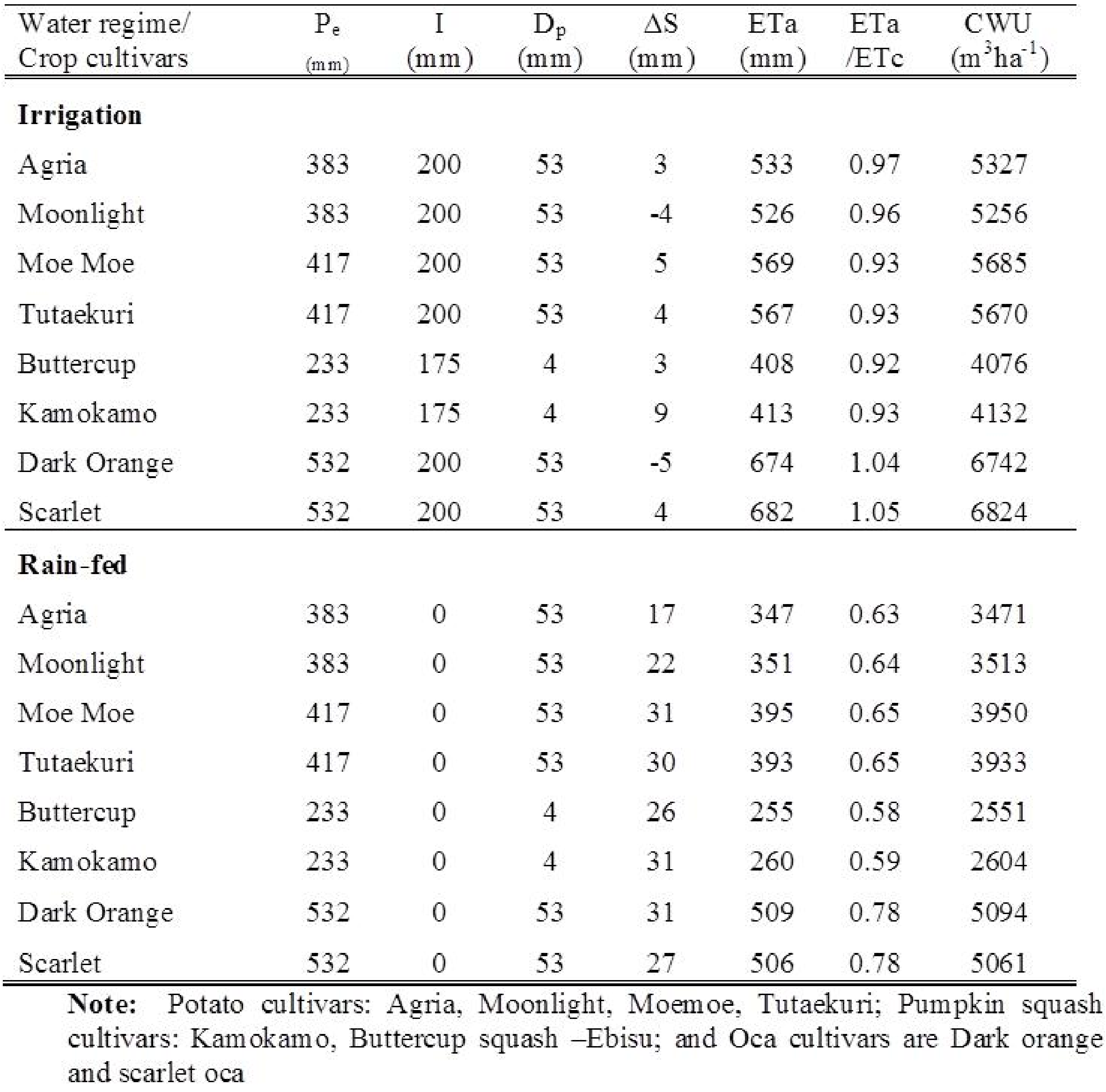
Appendix 3.3 Interaction between potato cultivar, irrigation and N on DMC%. Error bar represents ±SEM.



Appendix 3. 4 Specific gravity and tuber dry matter content (%) relationship for four potato cultivars grown in glasshouse, 2009



Appendix 4.4.1 Precipitation (Pe), irrigation (I), deep percolation (Dp), soil moisture change (ΔS), actual evapotranspiration (ETa), and crop water use [ETc or CWU = Pe + I –Dp + ΔS] per ha in mm from 10th Nov., 2009 to May, 2010



Water regime/ Crop cultivars	P_e (mm)	I (mm)	D_p (mm)	ΔS (mm)	ETa (mm)	ETa /ETc	CWU (m^3ha^{-1})
Irrigation							
Agria	383	200	53	3	533	0.97	5327
Moonlight	383	200	53	-4	526	0.96	5256
Moe Moe	417	200	53	5	569	0.93	5685
Tutaekuri	417	200	53	4	567	0.93	5670
Buttercup	233	175	4	3	408	0.92	4076
Kamokamo	233	175	4	9	413	0.93	4132
Dark Orange	532	200	53	-5	674	1.04	6742
Scarlet	532	200	53	4	682	1.05	6824
Rain-fed							
Agria	383	0	53	17	347	0.63	3471
Moonlight	383	0	53	22	351	0.64	3513
Moe Moe	417	0	53	31	395	0.65	3950
Tutaekuri	417	0	53	30	393	0.65	3933
Buttercup	233	0	4	26	255	0.58	2551
Kamokamo	233	0	4	31	260	0.59	2604
Dark Orange	532	0	53	31	509	0.78	5094
Scarlet	532	0	53	27	506	0.78	5061

Note: Potato cultivars: Agria, Moonlight, Moemoe, Tutaekuri; Pumpkin squash cultivars: Kamokamo, Buttercup squash –Ebisu; and Oca cultivars are Dark orange and scarlet oca

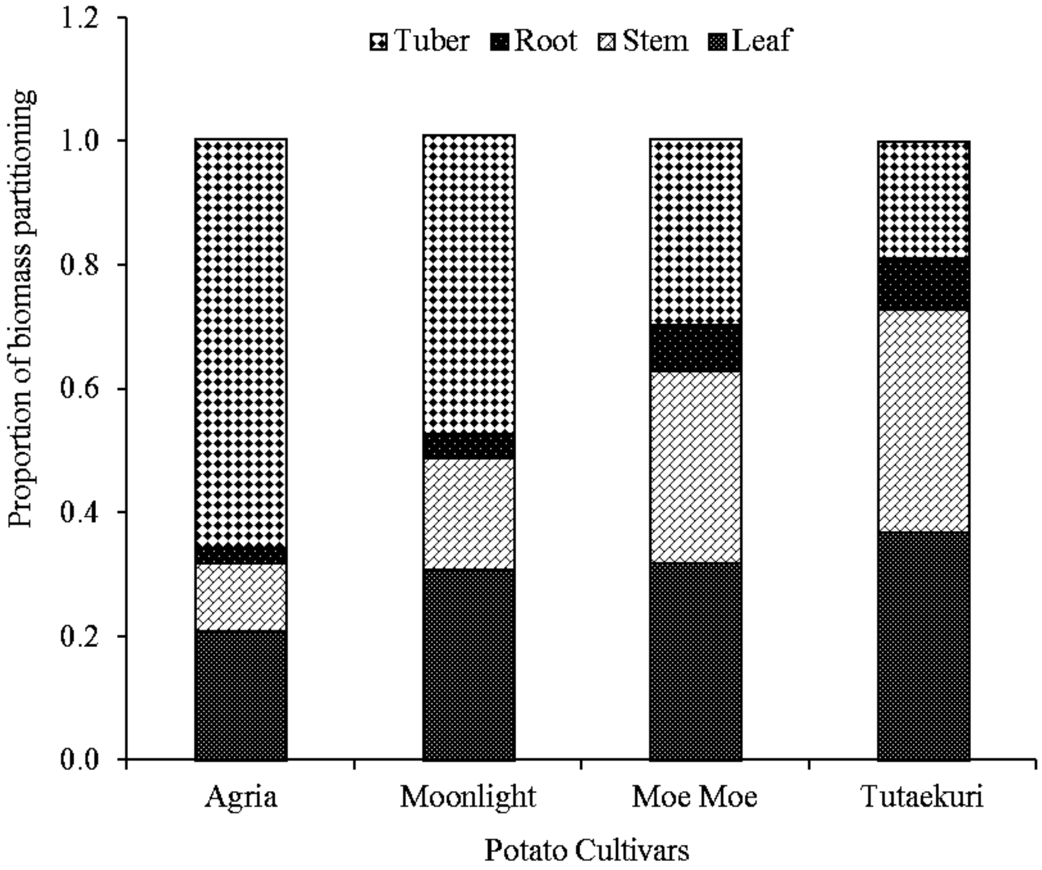
Appendix 4.4.2 Effect of irrigation and cultivars on volumetric soil moisture content (%) in the field, 4th January 2009 to 11th May, 2010

Water regime	Dates of Soil Moisture Measurements After Irrigation													
Cultivars	4 Jan.	7 Jan.	14 Jan.	5-Feb	22 Feb.	3-Mar	10-Mar	16-Mar	24-Mar	15-Apr	20-Apr	26-Apr	11-May	Mean
Irrigation														
Agria	27.0	33.1	30.0	25.9	26.9	39.4	33.8	28.8	33.4	34.3	29.8	28.0	25.6	30.5
Dark Orange	31.0	30.3	30.2	23.0	27.9	38.0	33.1	31.7	27.9	36.8	33.7	35.0	33.4	31.7
Buttercup	36.4	31.7	29.9	26.4	27.3	35.6	31.7	31.0	34.7					31.6
Kamokamo	36.6	28.3	29.1	24.6	25.1	35.2	29.1	26.6	32.1					29.6
Moe Moe	31.2	27.4	29.8	23.8	26.4	40.1	31.0	30.1	32.8	33.7	30.6	29.0	28.8	30.4
Moonlight	31.5	28.6	29.5	25.4	28.7	43.6	35.1	32.0	33.3	38.3	36.4	38.6	33.6	33.4
Scarlet	30.2	28.5	30.4	24.6	25.0	35.9	31.1	26.9	24.8	31.5	31.1	27.7	28.5	28.9
Tutaekuri	31.3	30.5	30.1	20.8	27.9	38.5	32.0	30.0	32.8	35.2	31.0	34.0	29.6	31.0
Rain-fed														
Agria	33.6	18.7	22.7	14.7	19.2	17.0	19.8	16.1	20.2	16.8	21.4	20.7	24.9	20.4
Dark Orange	33.2	18.5	21.6	20.9	21.1	20.3	20.8	20.9	22.5	20.4	21.3	20.8	18.0	21.6
Buttercup	36.3	21.3	23.7	20.7	20.0	24.7	17.3	14.4	23.4					22.4
Kamokamo	36.5	22.8	25.2	15.5	17.7	19.4	15.8	13.9	20.9					20.8
Moe Moe	30.3	21.5	21.8	13.8	16.6	18.2	16.9	16.1	23.6	17.5	22.1	12.6	14.6	18.9
Moonlight	34.7	24.4	20.9	18.6	21.0	26.9	20.9	16.6	18.4	19.3	20.3	20.3	23.9	22.0
Scarlet	35.5	20.7	23.4	21.3	21.2	23.3	21.5	16.6	18.1	18.7	21.6	16.6	21.9	21.6
Tutaekuri	35.5	19.6	21.8	19.2	18.2	19.7	18.9	15.5	20.1	15.1	20.5	20.8	20.6	20.4
Cv. (%)														14.62
Significance														
Water regime														
Cultivar														P<0.0001
Date														P<0.0001
Regime*Cultivar														P<0.0001
Date*Water Regime														P<0.05

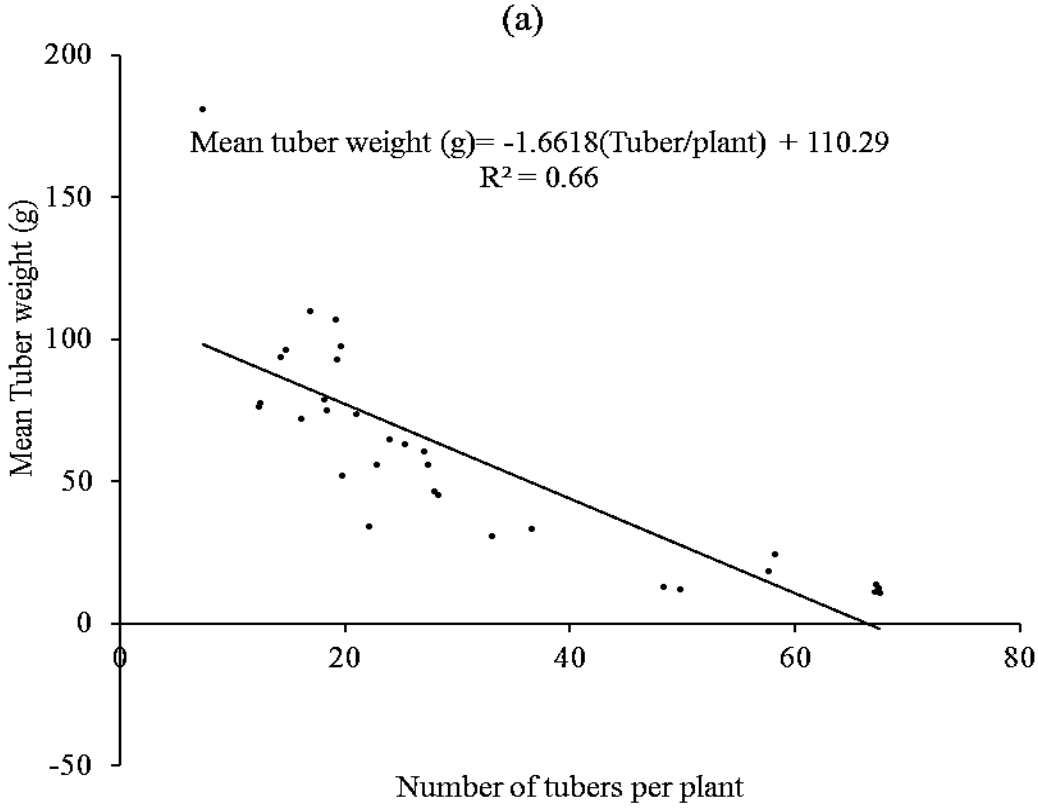
Appendix 4.4.3 Photosynthetic WUE (μmolCO_2/m molH_2O) and Net Photosynthesis (μmolCO_2 m^2 s^{-1}) for Taewa and modern potato cultivars under irrigation and rain-fed conditions at different days after emergence, 2010

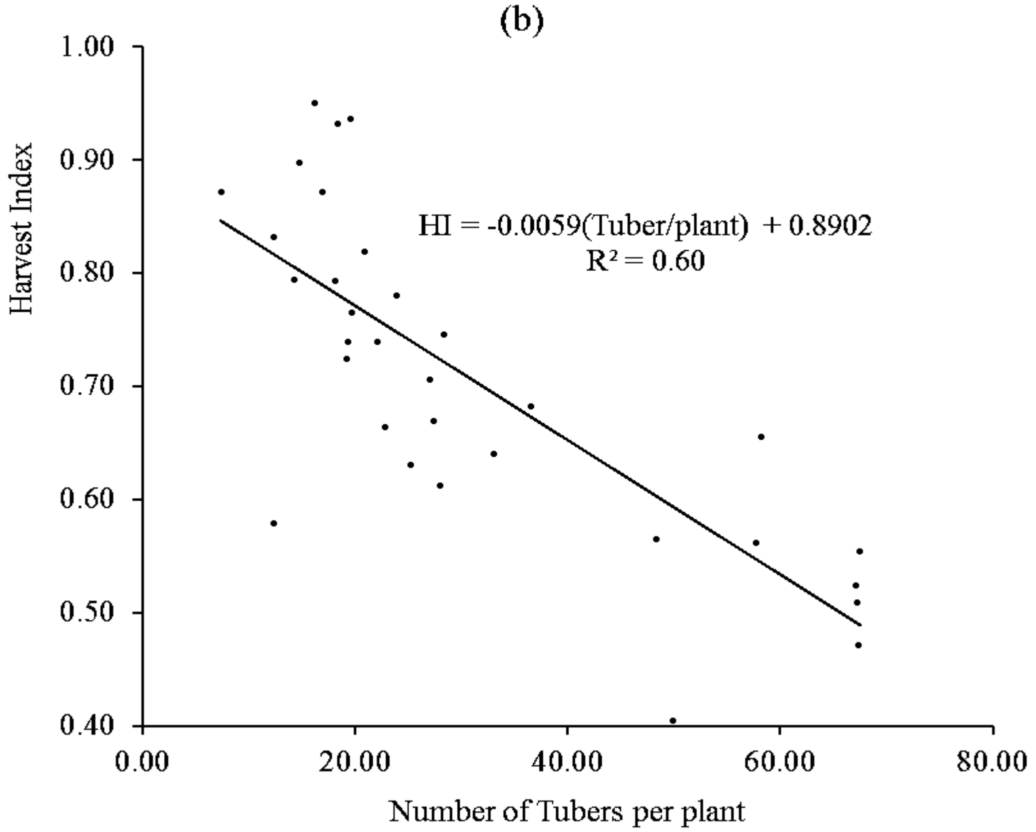
	Photosynthetic WUE (μmolCO_2/m molH_2O)					**Net Photosynthesis** (μmolCO_2 m^2 s^{-1})				
Water regime/	Days after emergence				Mean	Days after emergence				Mean
Cultivar	21	48	64	90	(n=4)	21	48	64	90	(n=4)
Irrigation (n=8)										
Agria	7.48	10.90	9.20	6.20	8.45	23.1	30.8	28.6	21.1	25.9
Moonlight	6.44	11.20	5.50	6.60	7.44	21.5	28.7	20.3	22.2	23.2
Moe Moe	4.46	10.90	10.50	7.40	8.32	17.8	28.8	26.5	25.2	24.6
Tutaekuri	7.08	9.20	6.40	6.60	7.32	19.4	25.3	23.3	19.5	21.9
Mean (n=16)	6.37	10.55	7.90	6.70	7.88	20.5	28.4	24.7	22.0	23.9
Rain-fed (n=8)										
Agria	4.34	8.01	5.80	6.20	6.09	13.6	19.4	19.6	18.5	17.8
Moonlight	1.78	8.80	4.70	6.80	5.52	6.4	19.8	13.8	20.3	15.1
Moe Moe	2.46	10.90	5.70	5.40	6.12	9.3	26.0	19.2	19.9	18.6
Tutaekuri	2.89	8.40	6.60	6.20	6.02	10.4	19.5	20.5	17.0	16.9
Mean (n=16)	2.87	9.03	5.70	6.15	5.94	9.9	21.2	18.3	18.9	17.1
Significance										
Cultivars	$P<0.05$	$P<0.05$	$P<0.05$	Ns	$P<0.001$	Ns	Ns	Ns	$P<0.05$	$P<0.0001$
Water regime	$P<0.0001$	$P<0.0001$	$P<0.001$	Ns	$P<0.0001$	$P<0.0001$	$P<0.0001$	$P<0.001$	$P<0.01$	$P<0.0001$
DAE					$P<0.0001$					$P<0.001$
±SEM	0.45	0.102	0.45	0.24	1.34	1.21	1.06	1.12	0.6	3.1

Appendix 4.4.4 Proportion of dry matter partitioning in four potato cultivars after 100 days from planting

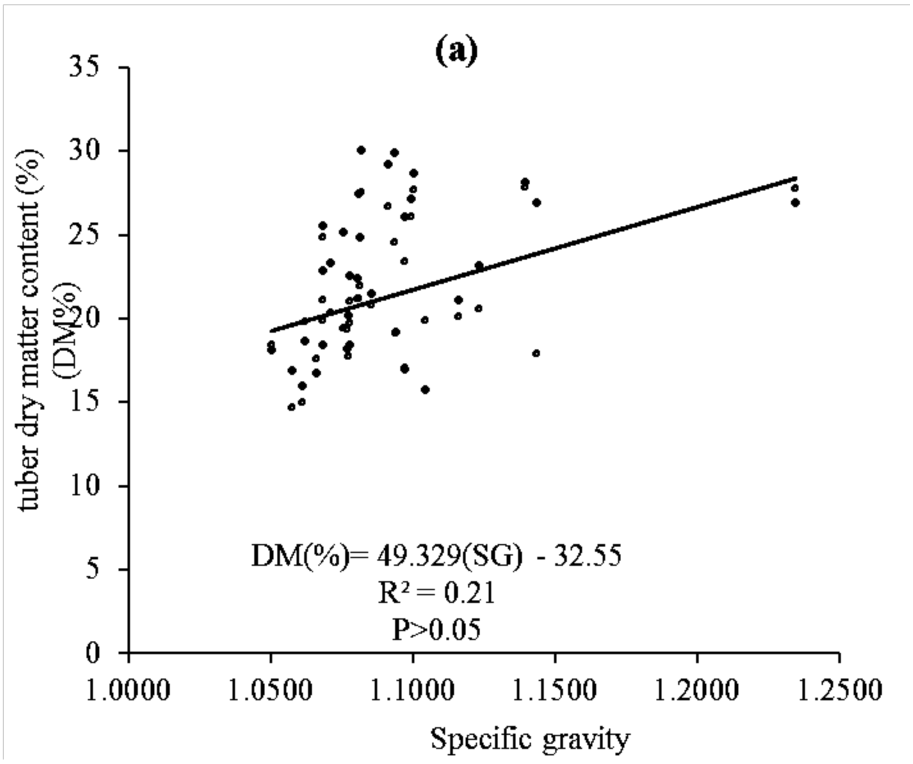


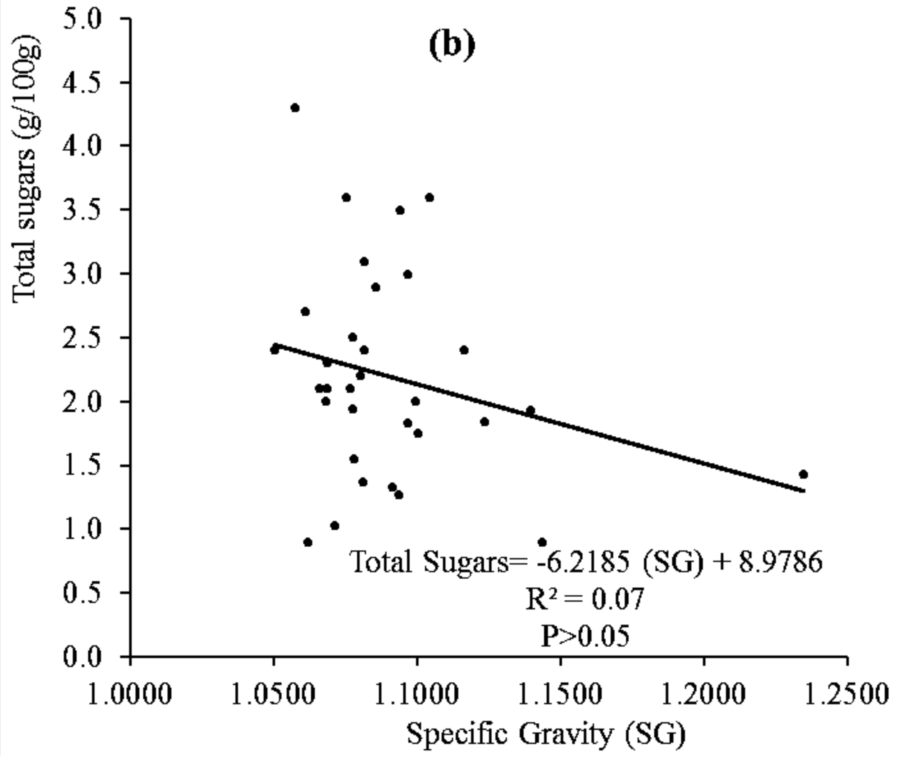
Appendix 4.4.5 Relationship of number of tuber with mean tuber weight (a) and harvest index (b)





Appendix 4.4.6 Relationships between (a) specific gravity and tuber dry matter content; (b) specific gravity and total sugars in potato cultivars



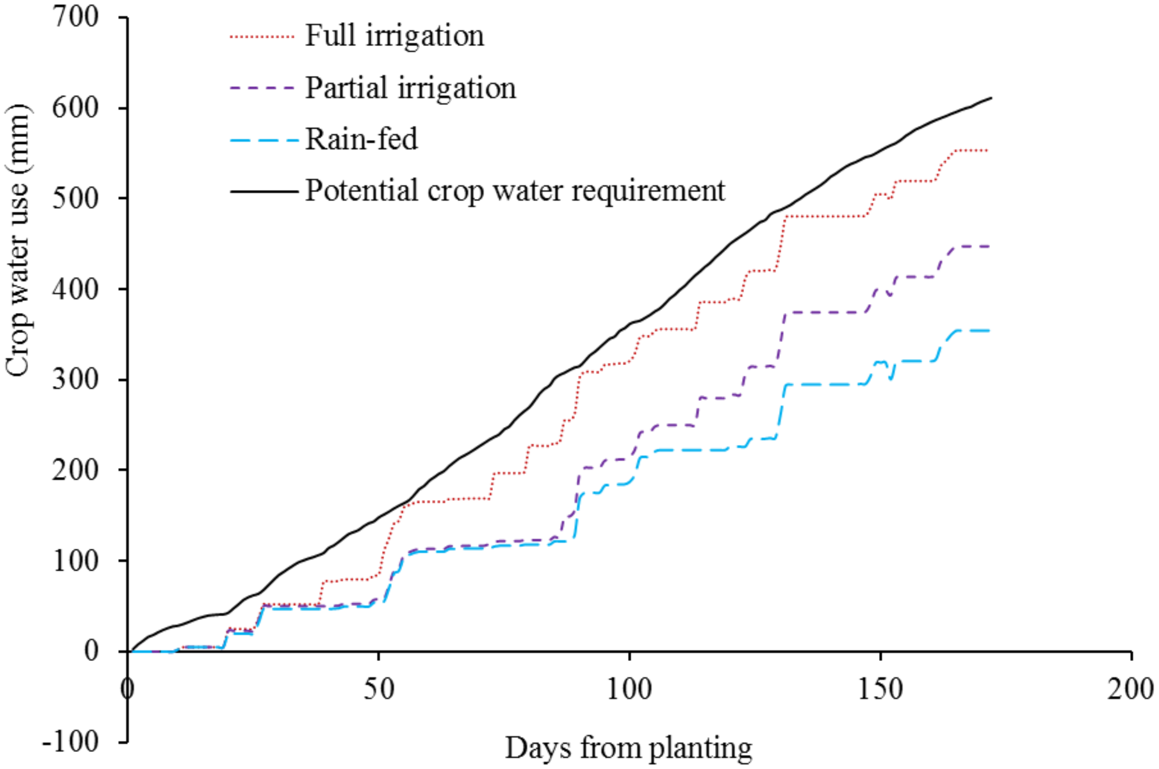


Appendix 5.1 (a) Effect of water regime, nitrogen and cultivars on volumetric soil moisture content (%) after 76 days from planting, 2010/2011

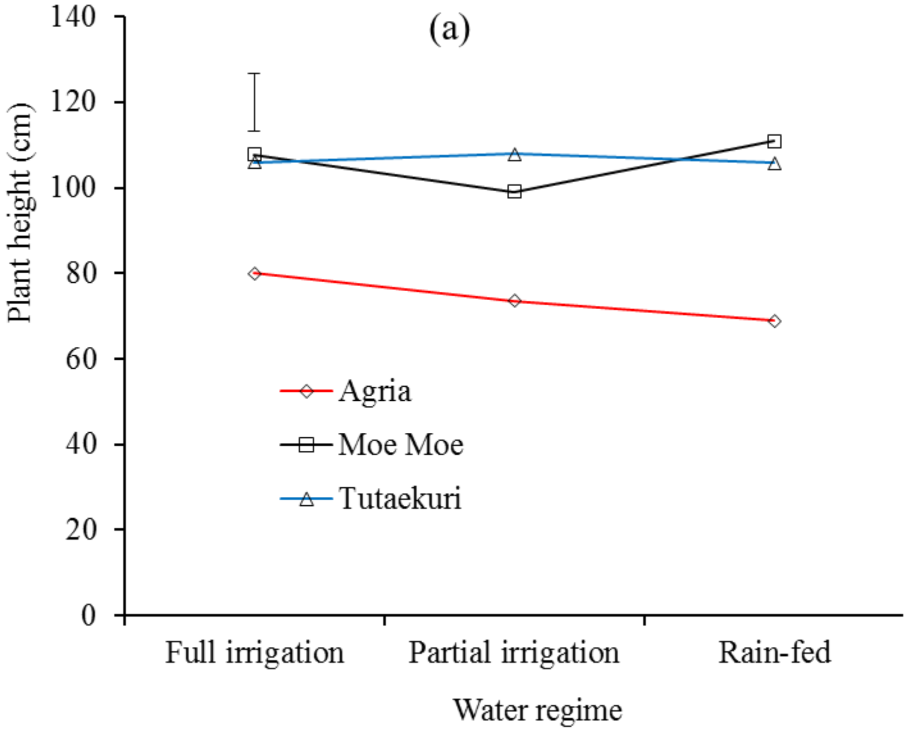
Water regime/ Potato cultivars	Nitrogen (KgN ha^{-1}) 80	240	Mean (n=128)	Mean (n = 52)
Full irrigation				
Agria	25.03	25.33	25.68^{b}	25.85^{a}
Moe Moe	25.02	25.00	25.03^{b}	
Tutaekuri	25.05	28.65	26.85^{a}	
Mean (n=192)	25.37	226.33		
Partial irrigation				
Agria	16.37	15.50	15.94^{b}	18.72^{b}
Moe Moe	19.37	20.13	20.03^{a}	
Tutaekuri	19.03	21.37	20.20^{a}	
Mean (n=192)	18.44	19.00		
Rain-fed				
Agria	14.65	14.03	14.34^{b}	15.31^{c}
Moe Moe	15.53	14.43	14.98^{b}	
Tutaekuri	18.30	14.95	16.63^{a}	
Mean (n=192)	16.16	14.47		
CV%				9.96
Interactions				
Cultivars (Cult.)				$p<0.001$
Water regime (WR)				$p<0.0001$
Nitrogen (N)				Ns
Water regimes*Cultivars				$p<0.05$
WR*Cultivars*N				$p<0.05$

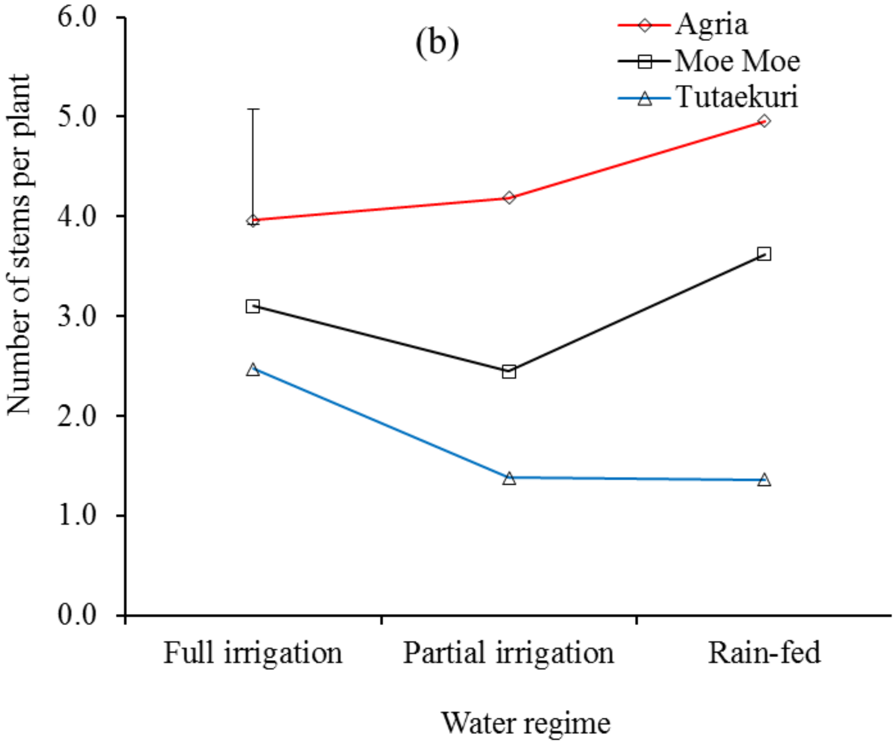
Note: Means with similar letters along column rows are not significantly different at 5% level of probability.

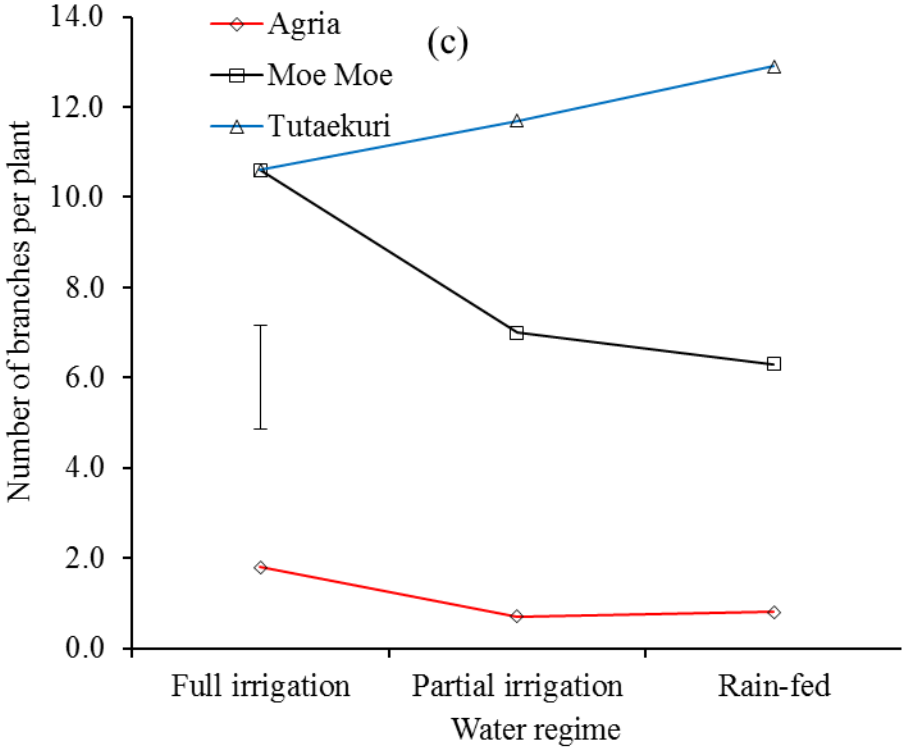
Appendix 5.1 (b) Cumulative potential evapotranspiration (mm) and crop water use (mm) in three water regimes in 2010/2011

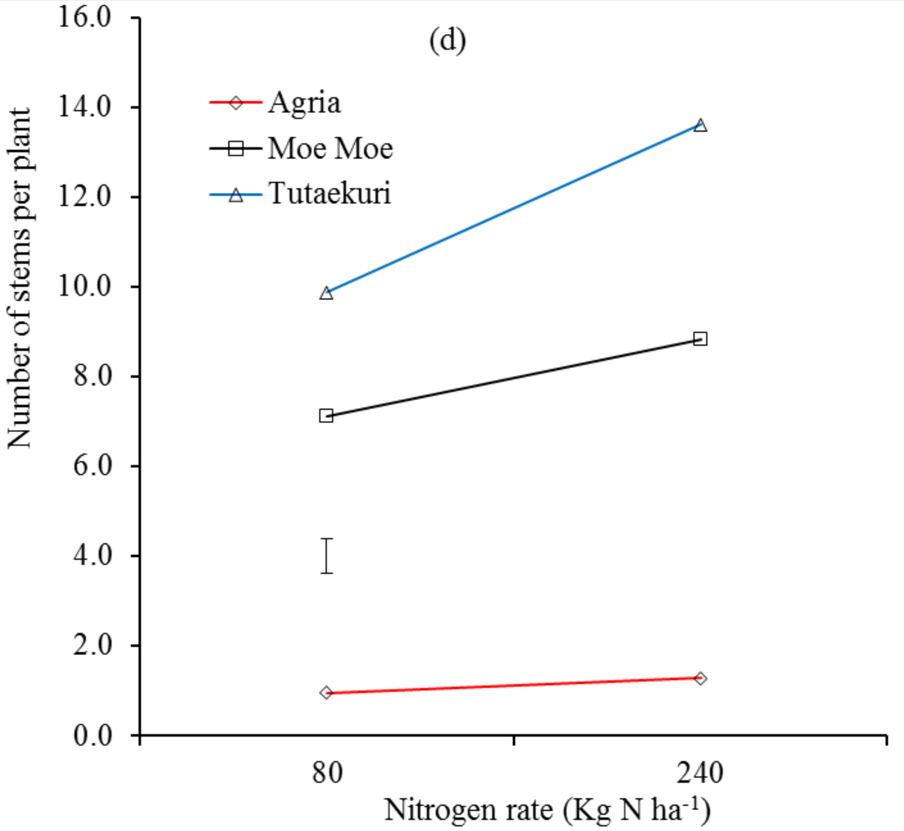


Appendix 5.2 Interaction between potato cultivars and water regime on plant height (a), stems per plant (b), number of branches per plant (c) and interaction between potato cultivars and N on stems per plant (d)

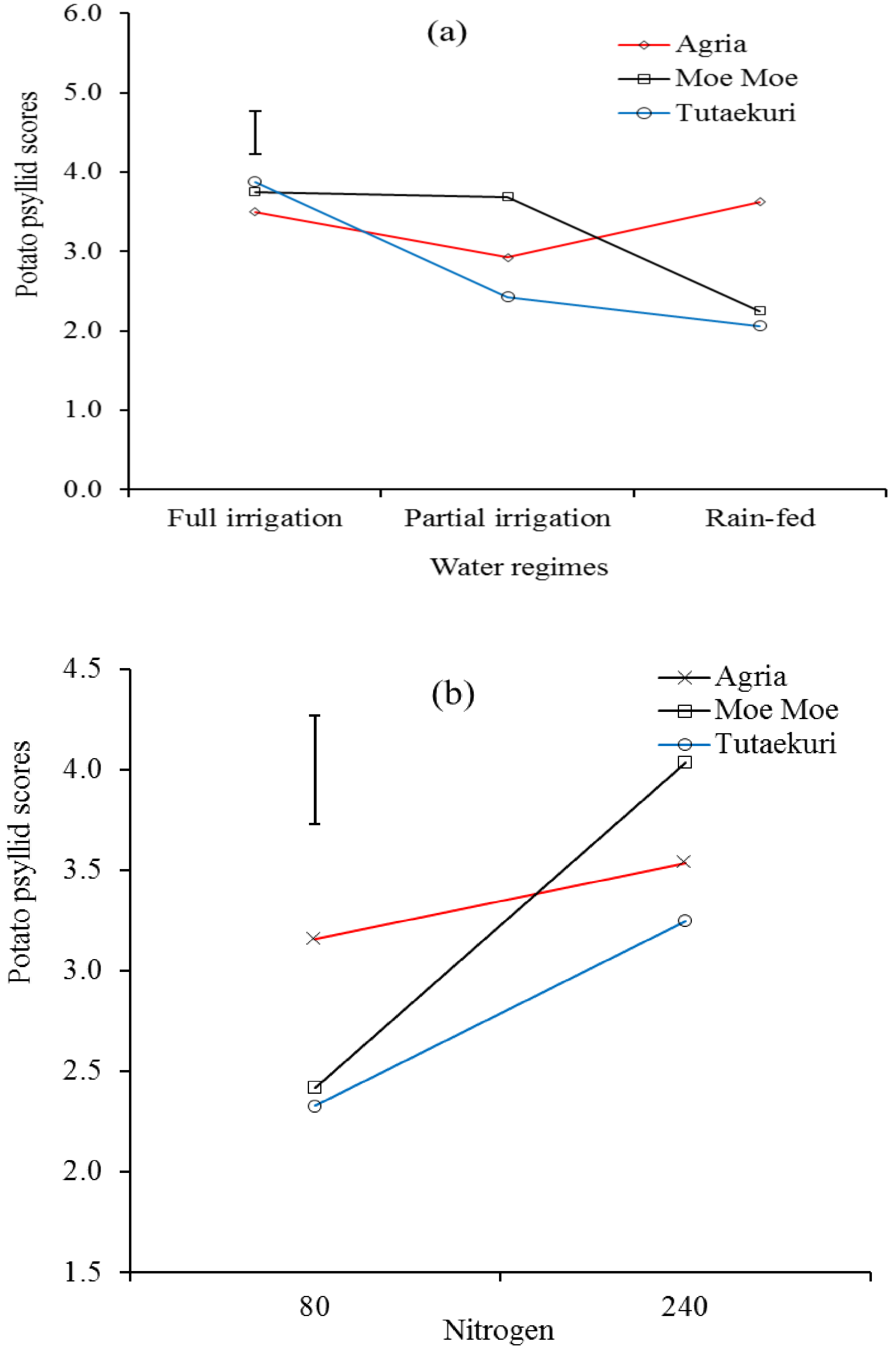




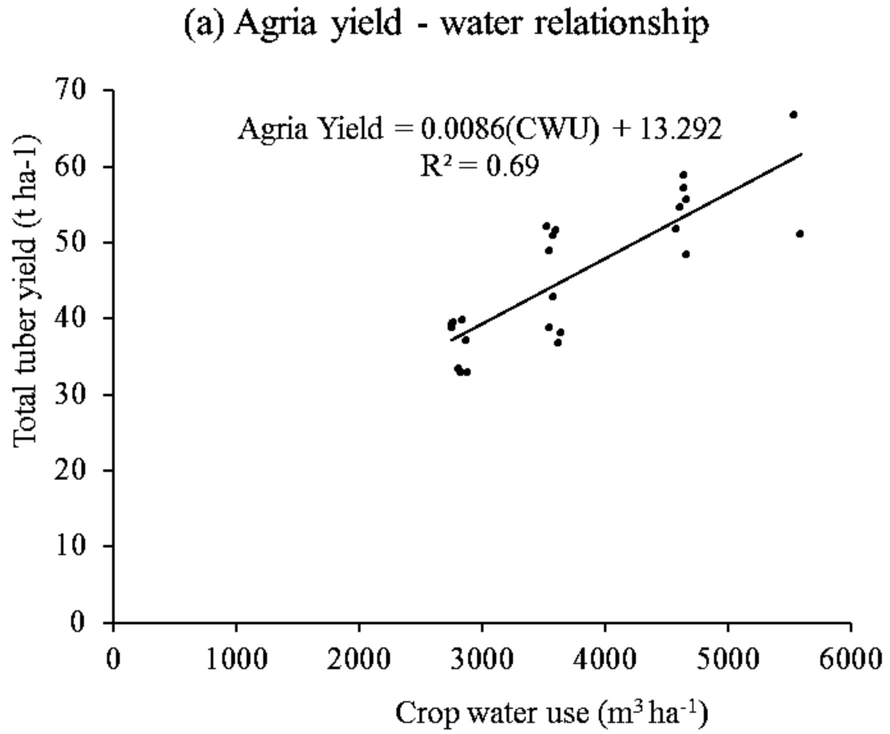

(c)
Agria
Moe Moe
Tutaekuri
Number of branches per plant
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Full irrigation
Partial irrigation
Rain-fed
Water regime

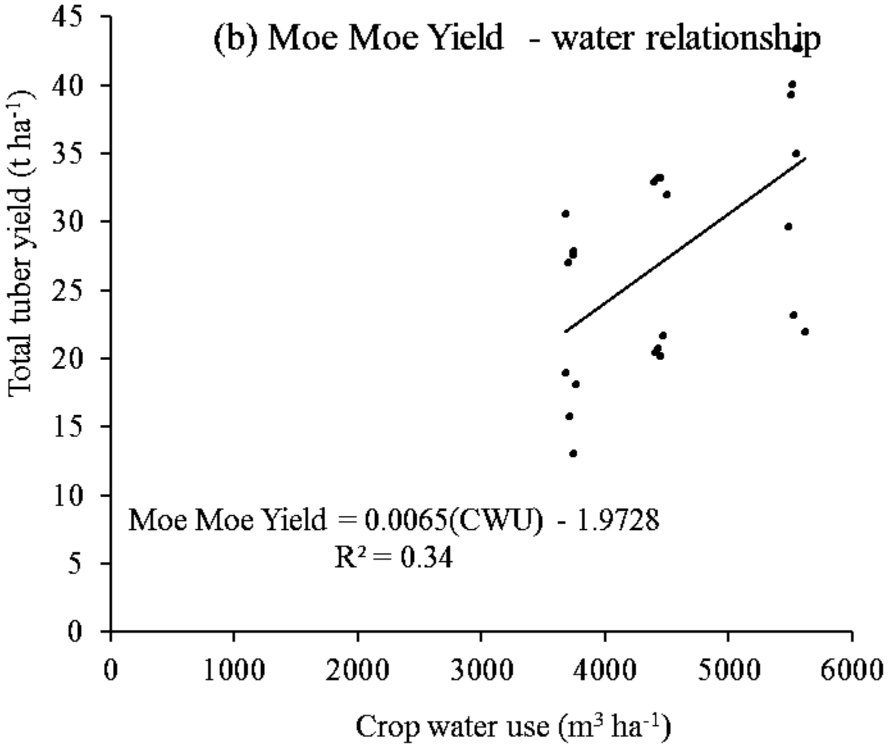

(d)
Agria
Moe Moe
Tutaekuri
Number of stems per plant
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
80
240
Nitrogen rate (Kg N ha^{-1})

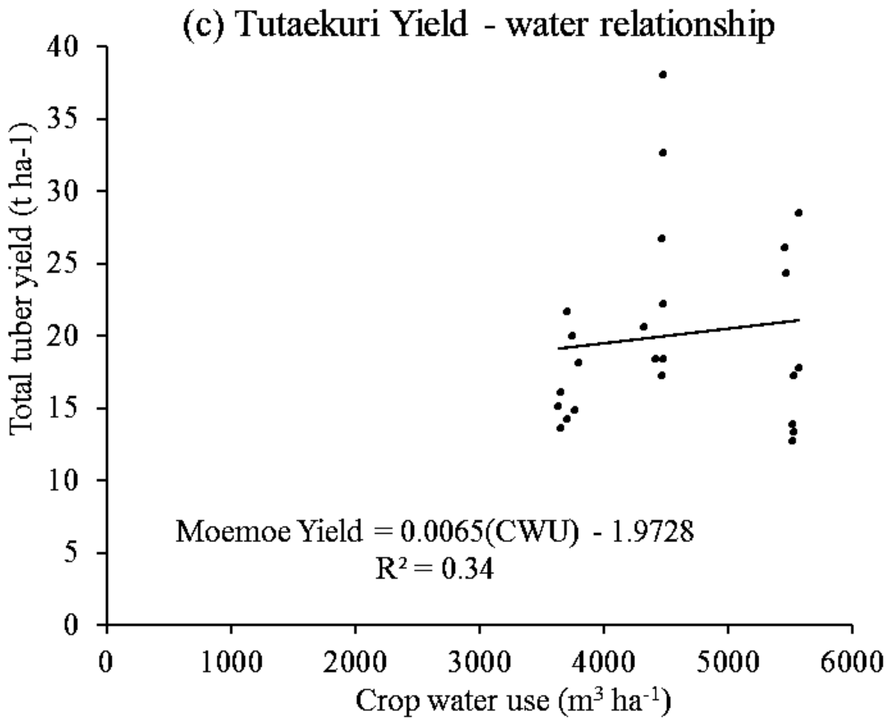
Appendix 5.3 Interaction between water regime*cultivar (a) and cultivar * nitrogen (b) on Tomato/Potato psyllid infestation. Error bar represents ±SEM.



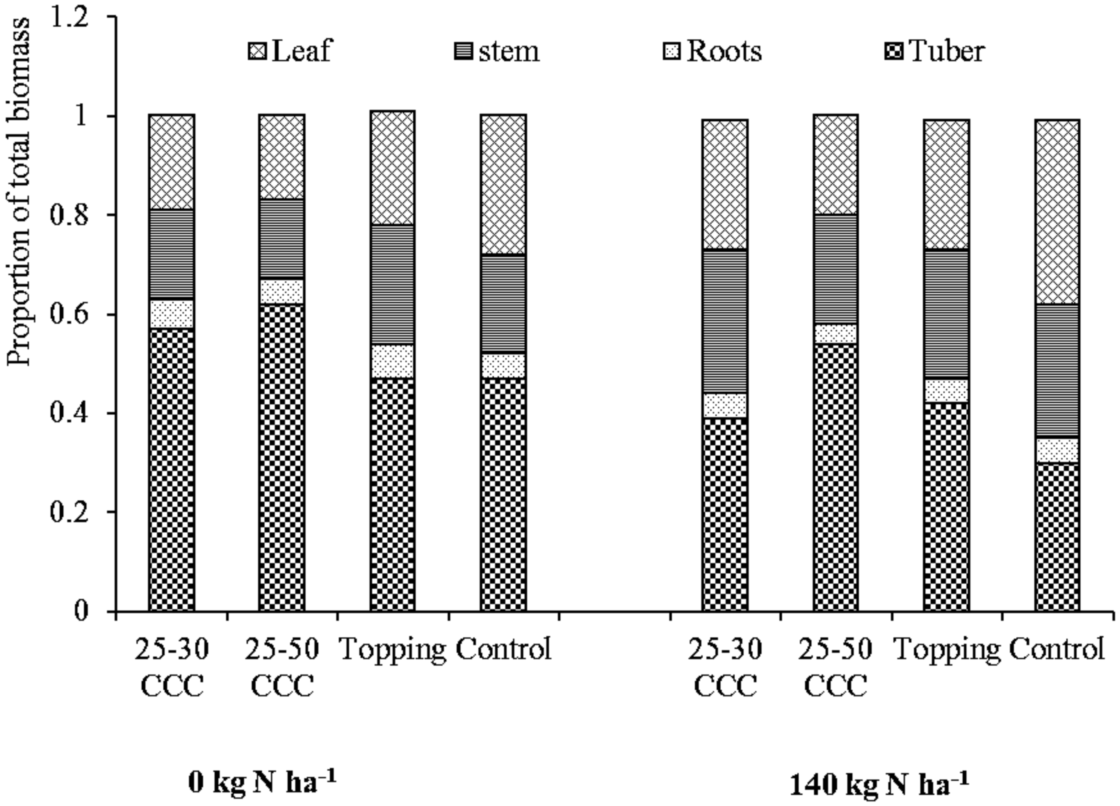
Appendix 5.4 Potato tuber yield-water relationship (a-c) and yield response factor, k_y (d-f)






(c) Tutaekuri Yield - water relationship
Total tuber yield (t ha-1)
40
35
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
Crop water use (m³ ha⁻¹)
Moemoe Yield = 0.0065(CWU) - 1.9728
R² = 0.34

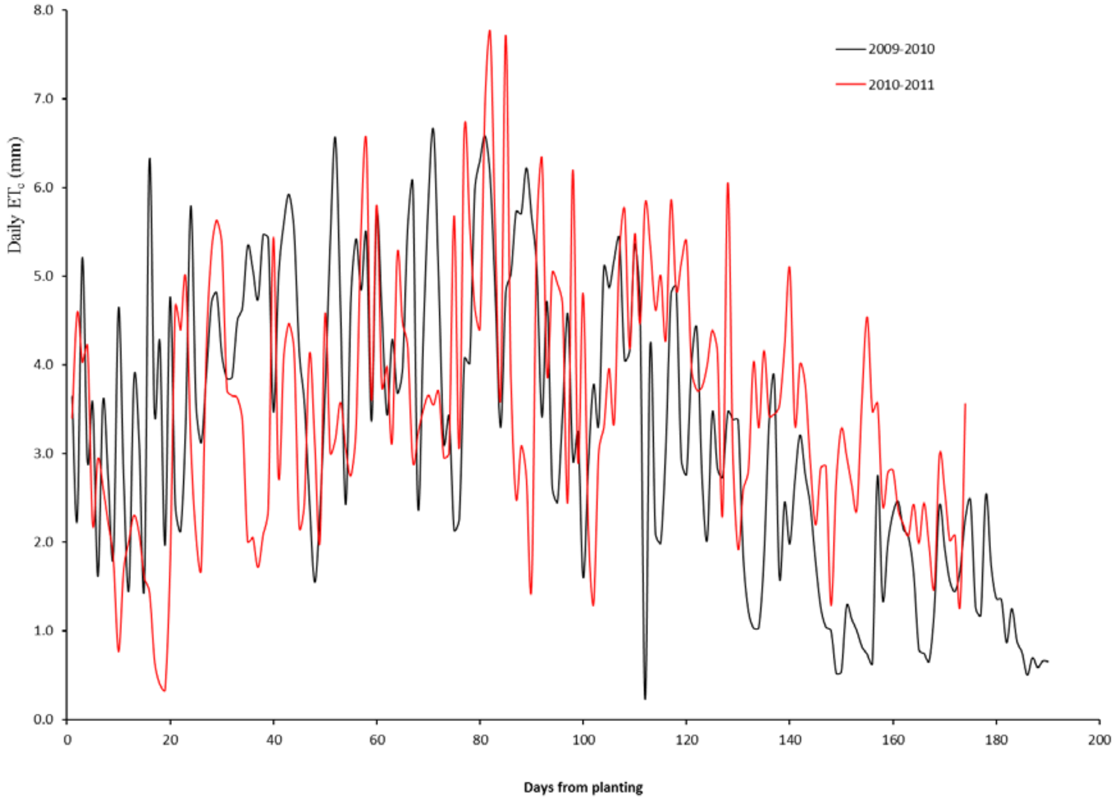
Appendix 6.1 Proportion of dry matter partition to leaves, stems, roots and tubers in Tutaekuri under different nitrogen and canopy manipulations



Appendix 6.2 The relationship of gaseous exchange parameters in Tutaekuri

	Net photosynthesis (A_n)	Stomata conductance (g_s)	Transpiration (T)	Leaf temperature (LT)	Internal carbon concentration
Photosynthetic WUE	r=0.78 P<0.0001	r=0.51 P<0.0001	r=0.45 P<0.01	r=-0.65 P<0.0001	R=-0.94 P<0.0001
A_n		r=0.91 P<0.0001	r=0.88 P<0.0001	r=-0.70 P<0.0001	r=-0.60 P<0.0001
g_s			r=0.97 P<0.0001	r=-0.65 P<0.0001	r=-0.22 Ns
T				r=-0.62 P<0.0001	r=-0.32 P<0.05
LT					r=0.40 P<0.05

Appendix 7. 1 Daily evapotranspiration during the two growing seasons, October 2009 to June 2010 and October 2010 to April, 2011 at Massey University, Palmerston North Campus, New Zealand.



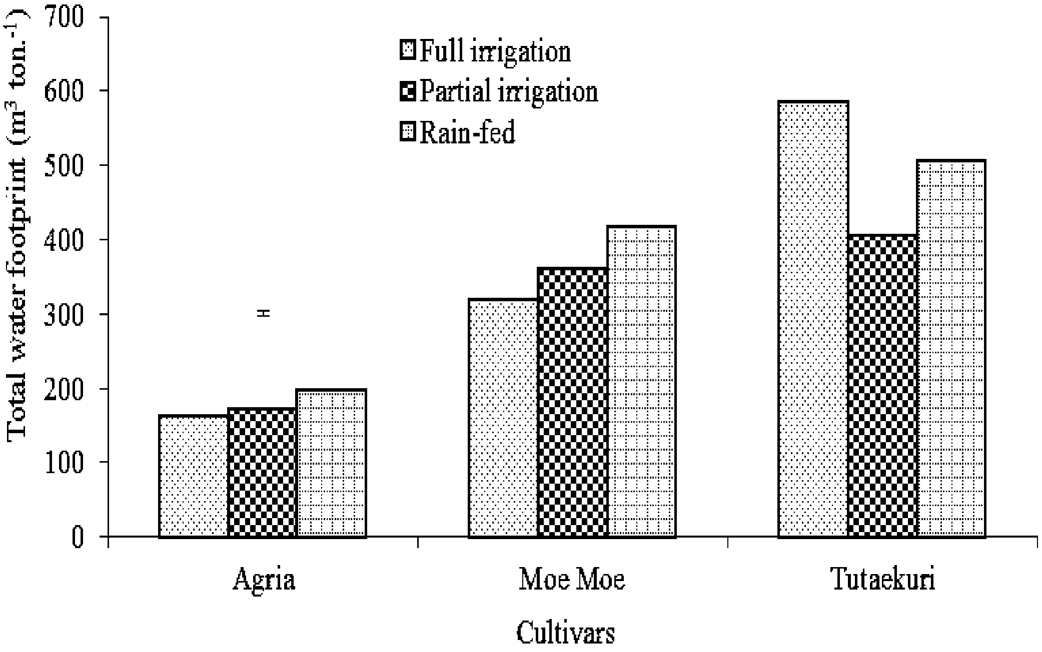
Appendix 7. 2 Difference in Taewa tuber yields between two seasons (2009-2010 and 2010-2011) under same water regimes

Year	2009-2010	2010-2011			Tuber Yield Change From 2009/2010 to 2010/2011
Water regime/	Mean Yield	Nitrogen (t ha^{-1})		Mean Yield	
Cultivars	(t ha^{-1})	80	240	(t ha^{-1})	(t ha^{-1})
Full irrigation					
Agria	51.7	51.5	59.6	55.6	3.9
Moonlight	59.4	-	-	-	-
Moe Moe	52.6	41.1	27.4	34.3	-18.3
Tutaekuri	27.6	24.1	14.3	19.2	-8.4
Mean	47.8	38.9	33.8	36.3	-11.5
Partial Irrigation					
Agria	-	41.1	48.8	45.0	-
Moe Moe	-	32.8	20.7	26.8	-
Tutaekuri	-	29.9	18.6	24.3	-
Mean	-	34.6	29.4	32.0	-
Rain-fed					
Agria	34.0	38.9	34.5	36.7	2.7
Moonlight	39.7	-	-	-	-
Moe Moe	40.1	28.2	16.4	22.3	-17.8
Tutaekuri	30.0	19.0	14.4	16.7	-13.3
Mean	36.0	28.7	21.8	25.2	10.8

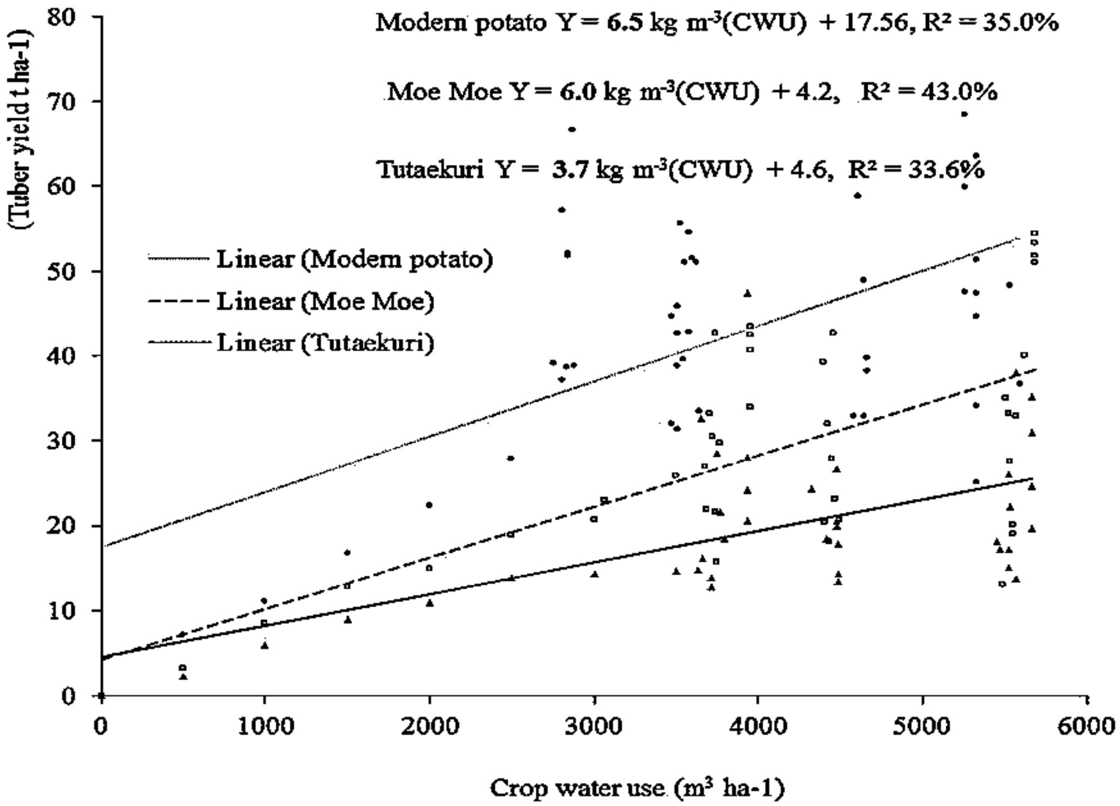
Appendix 7.3 Spray schedule and type of pesticides used in 2010/2011

Spray	Product + Active Ingredient	Insecticide Chemical Group	Target Pests	Notes	Date of spray
Spray 1	Avid (abamectin)	IRAC MoA 6 (Avermectins)	Mite pests + Leaf Miners, psyllid	Compatible + IPM	9th Dec., 2010
Spray 2	Confidor (imidacloprid)	IRAC MoA 4A (Neonicotinoid)	Aphids	w/ fungicides	22nd Dec., 2010
Spray 3	Avid (abamectin) +Bravo	IRAC MoA 6 (Avermectins)	Mite pests + Leaf Miners, psyllid	Compatible + IPM	4th Jan., 2011
Spray 4	Confidor (imidacloprid)+Bravo	IRAC MoA 4A (Neonicotinoid)	Aphids	w/ fungicides	15th Jan., 2011
Spray 5	Avid (abamectin) +Bravo	IRAC MoA 6 (Avermectins)	Mite pests + Leaf Miners, psyllids	Compatible + IPM	26th Jan., 2011
Spray 6	Confidor (imidacloprid)+Bravo	IRAC MoA 4A (Neonicotinoid)	Aphids+psyllid	w/ fungicides	6th Feb., 2010
Spray 7	Avid (abamectin) +Bravo	IRAC MoA 6 (Avermectins)	Mite pests + Leaf Miners, psyllid	Compatible + IPM	21st Feb., 2011
Spray 8	Confidor (imidacloprid)+Bravo	IRAC MoA 4A (Neonicotinoid)	Aphids+psyllid	w/ fungicides	14th Mar., 2011

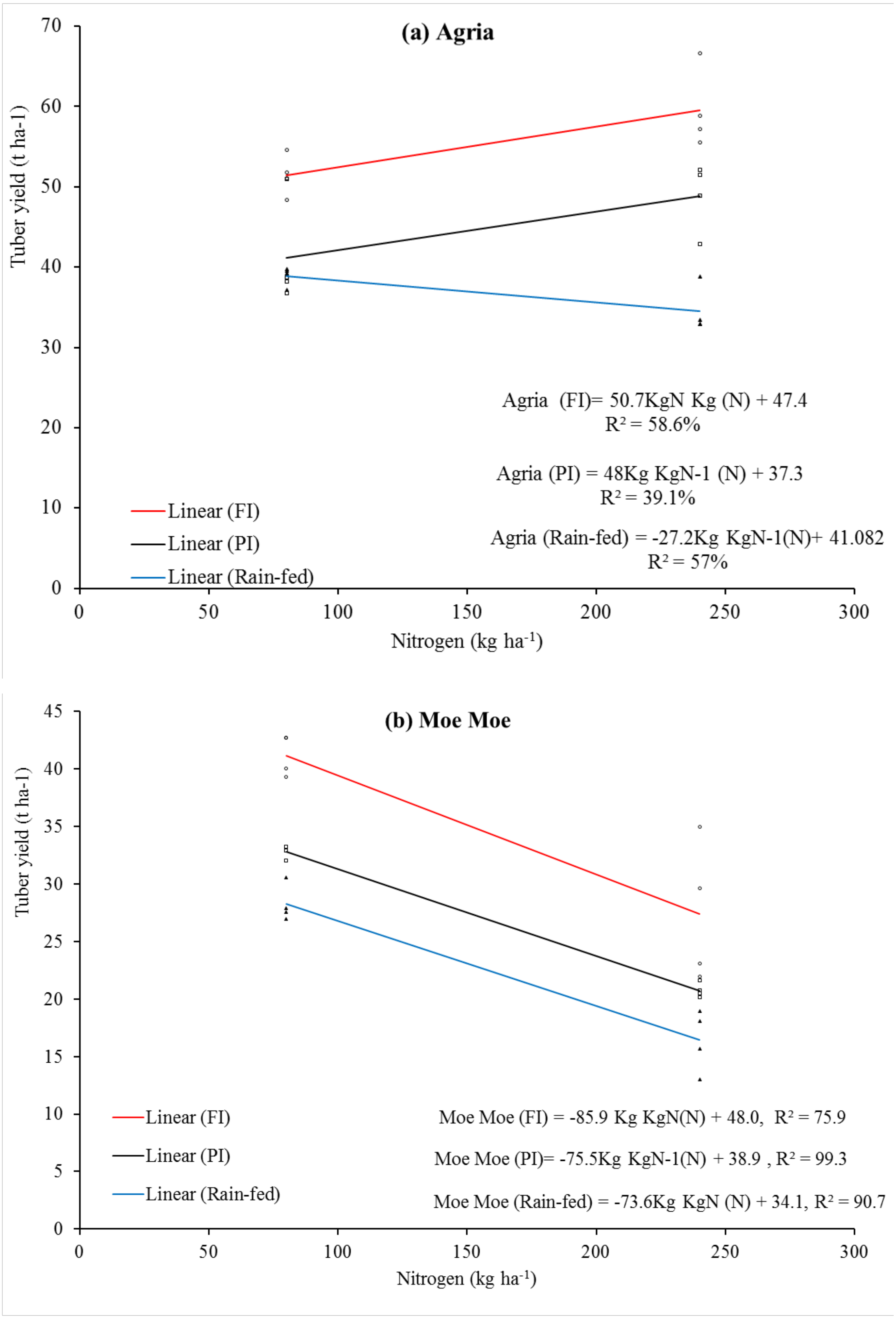
Appendix 7. 4 Total water footprints of growing Taewa and modern potato cultivars under different irrigation regimes, 2010/2011. Error bar represent ±SEM.

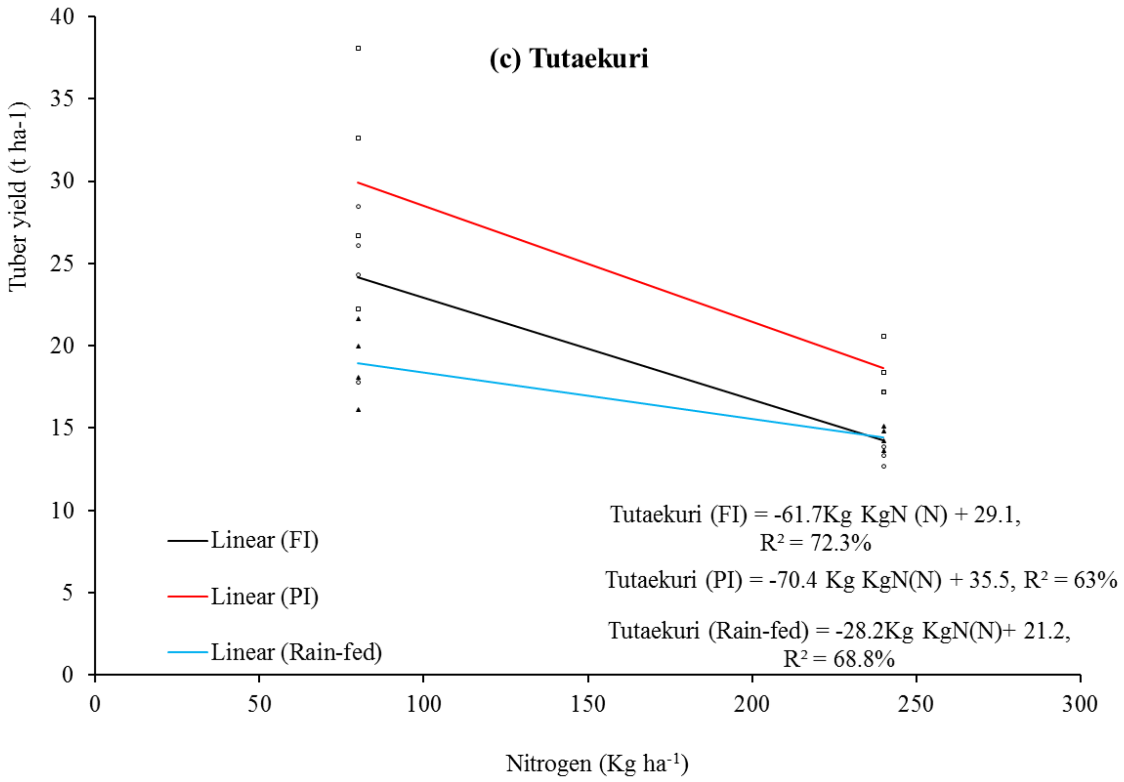


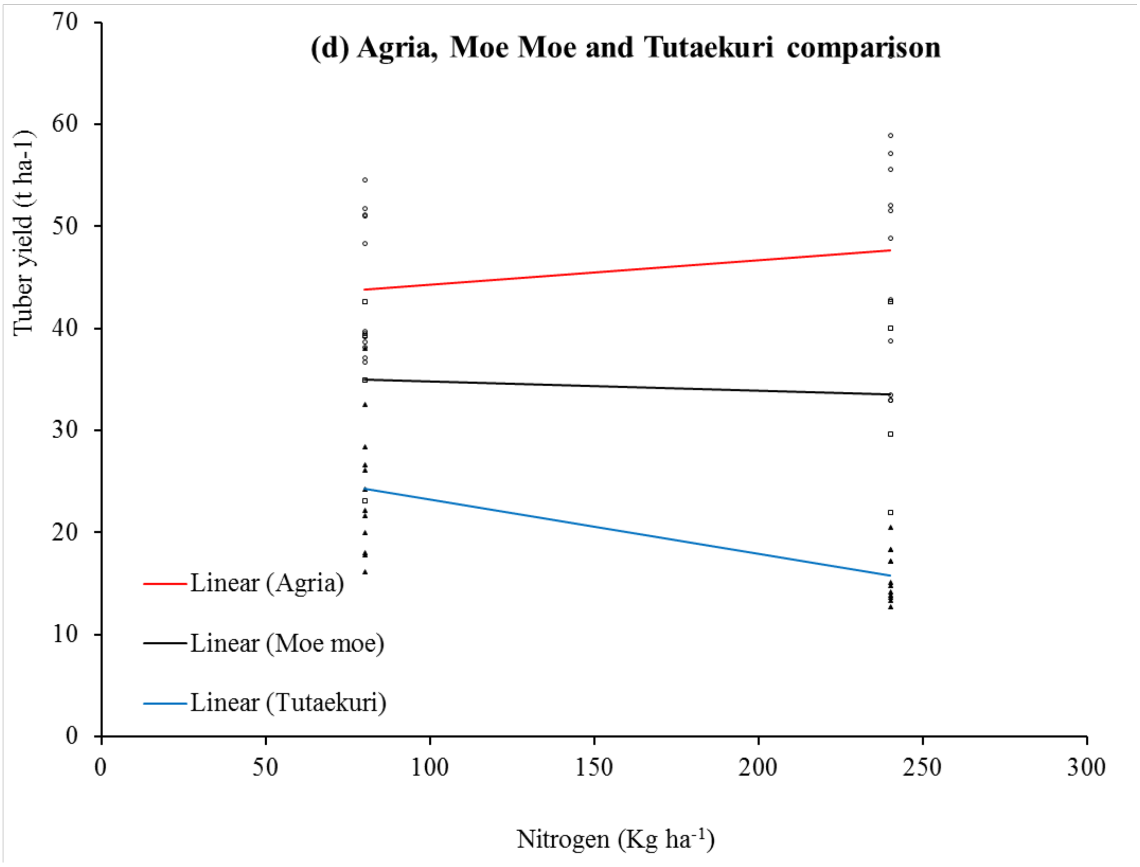
Appendix 7. 5 Optimal WUE benchmarks in Taewa and modern potato based on 2009-2010 and 2010-2011 studies



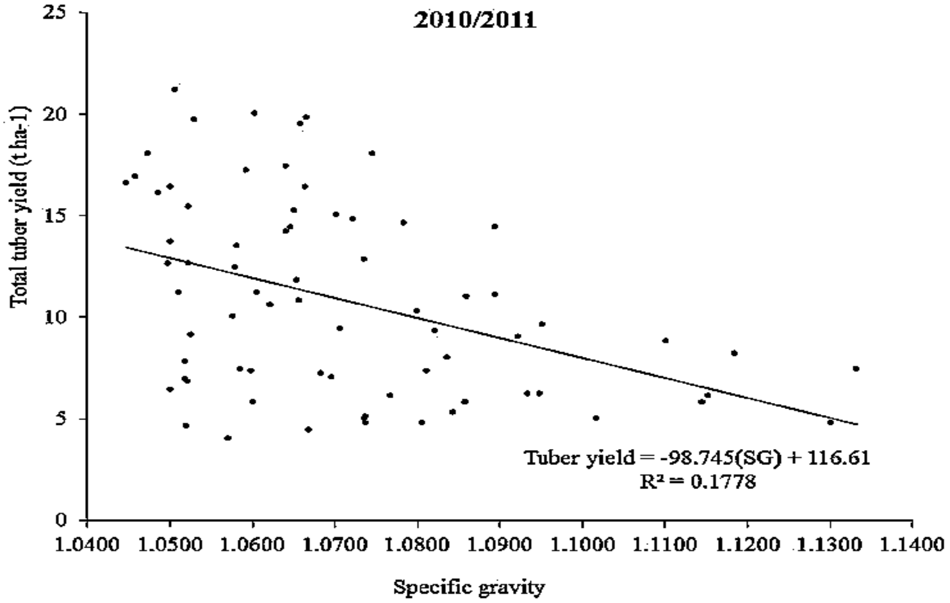
Appendix 7. 6 (abcd) Marginal productivity of Taewa and modern potato as affected by amount of N and water regime

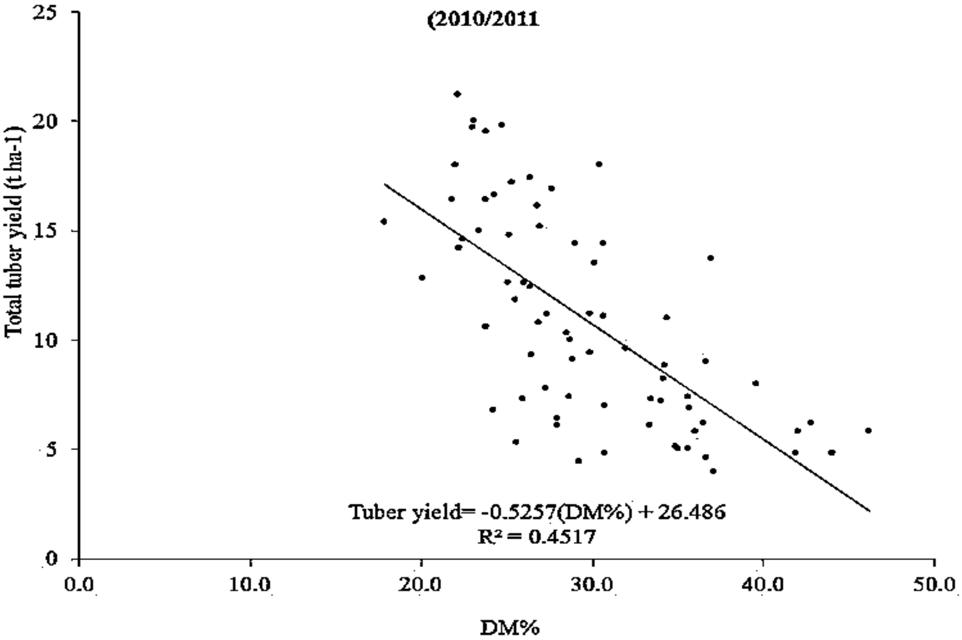



(c) Tutaekuri
Tuber yield (t ha-1)
40
35
30
25
20
15
10
5
0
0
50
100
150
200
250
300
Nitrogen (Kg ha-1)
Linear (FI)
Linear (PI)
Linear (Rain-fed)
Tutaekuri (FI) = -61.7Kg KgN (N) + 29.1, R² = 72.3%
Tutaekuri (PI) = -70.4 Kg KgN(N) + 35.5, R² = 63%
Tutaekuri (Rain-fed) = -28.2Kg KgN(N)+ 21.2, R² = 68.8%


(d) Agria, Moe Moe and Tutaekuri comparison
Tuber yield (t ha-1)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
Nitrogen (Kg ha-1)
Linear (Agria)
Linear (Moe moe)
Linear (Tutaekuri)

Appendix 7. 7 The relationship between total tuber and specific gravity (SG) and tuber dry matter content (DM %).





Appendix 7.8 The economic feasibility of Taewa in relation to irrigation investments

The adoption of irrigation for Taewa cannot be relevant, if the achievement of increased yield and water conservation does not produce gains within the agricultural production and biological economies of New Zealand. Economic feasibility is essential, given that an irrigation system for Taewa would need extra investments in irrigation equipment and operation for Taewa, compared to rain-fed production. Apart from determining strategies for improving Taewa production, this section assesses the impact of bringing irrigation into Taewa production: and its economic returns. An interpretation of Taewa yield into an applicable economic value, in comparison to modern potato cultivars, will help irrigation policy makers and Taewa growers to make informed investment decisions. The following section estimates fixed and annual operating costs and expected returns, based on a 5 ha small scale irrigation using a Trail Travel Irrigator and it discusses the economic implications of the system on Taewa production in New Zealand.

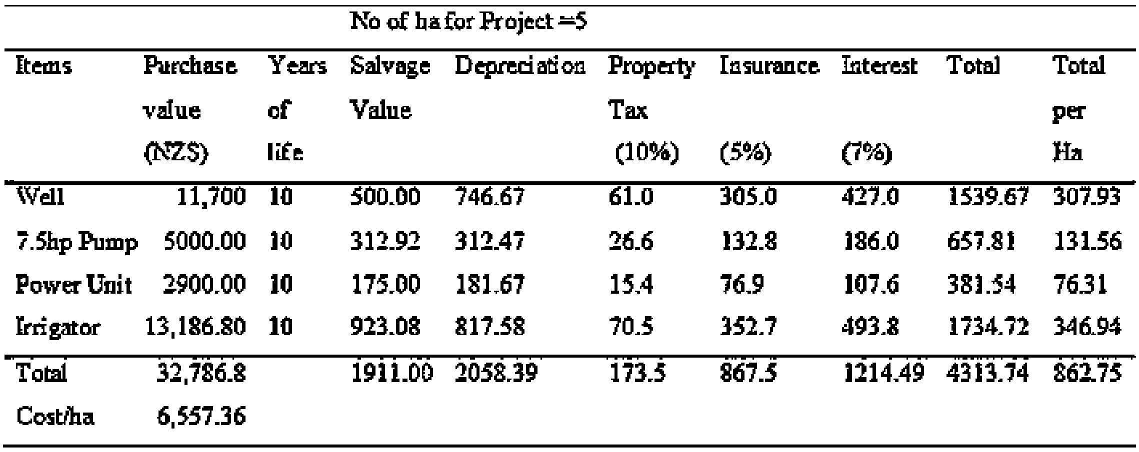
7.8.1 Method of investment analysis

This investment analysis is based on a net profit value analysis (NPV), referred to as the total of present value of single project cash flows of the same unit (FAO, 1997a). Net profit value was determined based on a Trail Travel irrigator system investment costing NZ$32,786.80 at 5 ha (NZ$6557.36/ha) (Table 7.8.1) and annual irrigation related operation costs ranging from NZ$1283.2 – NZ$1580.70 (Table 7.8.2). The analysis focuses on extra marketable yield increase (thus the difference between partial or full irrigation and rain-fed marketable yield) in three potato cultivar enterprises. The production system is a combination of crop enterprises, with full irrigation or partial irrigation under low or high N levels, compared to a rain-fed system under low or high N levels (Table 7.8.3). Each crop enterprise (Agria, Moe Moe, and Tutaekuri) had four batches of the production system to be assessed: two under full irrigation (low and high N) and two under partial irrigation (low and high N).

At the beginning, the initial present value for all production systems was determined as additional annual revenue. However, only the production system with the highest additional annual revenue per ha, from irrigation in the 1st year of each crop enterprise, was finally selected for NPV evaluation (Table 7.8.3). Subsequently, the last three NPVs presented are based on the best three selected production systems: one from each cultivar (Table 7.8.3).

Potato prices for New Zealand fluctuate within seasons and over years. However, prices also vary within potato varieties, with Taewa fetching more than 2.5 times that of modern potato varieties, in local markets and super markets. Over the past five to eight years, the price for modern potato at the farm gate has ranged from NZ$200 - 300 per tonne, with a weighted average of NZ$285 per tonne, in 2004, to NZ$300 - 400 per tonne, with a weighted average of NZ$385 per tonne, based on the assumption that 85% of the crop held a high price and 15% held a low price (Table 7.8.3). Unfortunately, Taewa has no marked price based per tonne at the farm gate and for the sake of this analysis a Taewa farm gate price of NZ$962 per tonne has been used, based on the assumption that its price at a local market is >2.5 times that of modern potato. The cost of irrigation in New Zealand is NZ$2 mm^{-1} ha^{-1}, according to Hedley *et al.* (2009a).

Table 7.8.1 Small scale irrigation system: investment and annual fixed cost estimates in NZ$.



No of ha for Project =5

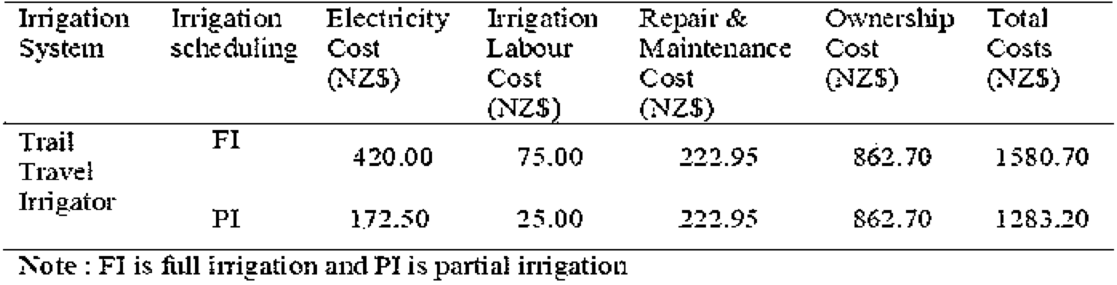
Items	Purchase value (NZ$)	Years of life	Salvage Value	Depreciation	Property Tax (10%)	Insurance (5%)	Interest (7%)	Total	Total per Ha
Well	11,700	10	500.00	746.67	61.0	305.0	427.0	1539.67	307.93
7.5hp Pump	5000.00	10	312.92	312.47	26.6	132.8	186.0	657.81	131.56
Power Unit	2900.00	10	175.00	181.67	15.4	76.9	107.6	381.54	76.31
Irrigator	13,186.80	10	923.08	817.58	70.5	352.7	493.8	1734.72	346.94
Total	32,786.8		1911.00	2058.39	173.5	867.5	1214.49	4313.74	862.75
Cost/ha	6,557.36								

Financial feasibility measures on variable irrigation costs are based on the methods used by AgriLINK NZ Ltd to calculate an economic analysis of potato production. All calculations were based on 1 ha, with the assumption of a 10 year investment at 10% interest rate. The NPV was calculated by subtracting the present value of cost from the present value of benefits, according to FAO (1997a), as presented in the equation below.

$$NPV = \sum_{t=0}^{n} \frac{Ct}{(I+r)t} \qquad \text{Equation 7.1}$$

Where: NPV= net present value; C = net cash flows received at the end of year t; I= the initial investment outlay; r= the discount rate/interest rate; and t = the project's duration in years (from zero to n).

Table 7.8.2 Annual ownership and operation costs for irrigation systems at full and partial irrigation scheduling



Irrigation System	Irrigation scheduling	Electricity Cost (NZ$)	Irrigation Labour Cost (NZ$)	Repair & Maintenance Cost (NZ$)	Ownership Cost (NZ$)	Total Costs (NZ$)
Trail Travel Irrigator	FI	420.00	75.00	222.95	862.70	1580.70
	PI	172.50	25.00	222.95	862.70	1283.20

Note : FI is full irrigation and PI is partial irrigation

7.8.2 Economics of irrigation on Taewa

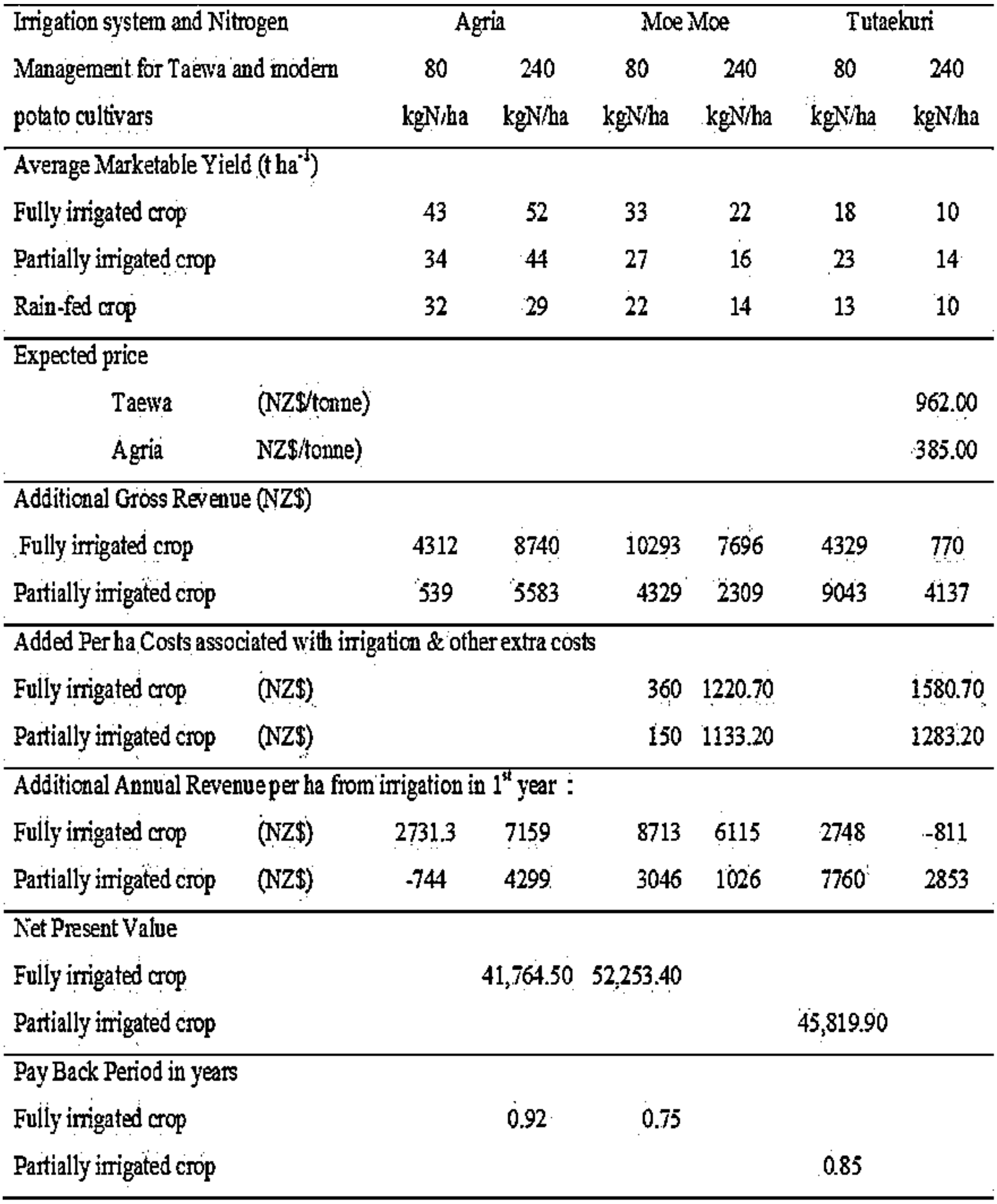
Table 7.8.3 indicates that irrigation increased the marketable tuber yield in all twelve combinations of the production system. Agria had the highest marginal marketable yield increase of 22.7 t ha^{-1} under full irrigation and 240 kgN ha^{-1} production systems (52 t ha^{-1} less 29.3 t ha^{-1}). The highest marketable yield increase for Moe Moe was 10.7 t ha^{-1} under full irrigation and 80 kgN ha^{-1} production systems (33 t ha^{-1} less 22.3 t ha^{-1}). The highest marketable yield increase for Tutaekuri was 9.4 t ha^{-1} under partial irrigation and 80 kgN ha^{-1} production systems (23 t ha^{-1} less 13.6 t ha^{-1}). However, amongst the three enterprises aforementioned, Moe Moe, had the highest additional gross revenue on investment income (NZ$10,293); present value or additional annual revenue per ha from irrigation in the 1st year (NZ$ 8713); net present value (NZ52, 253.40) (Table 7.8.3; Table 7.8.4); and shortest repayment period (0.75 years), due to its high value and intermediate marginal yield increase with full irrigation and low N.

Regardless of the highest yield increase with full irrigation and high N in modern potato, Agria, it was the least economic crop enterprise in relation to gross revenue on investment income (NZ$8,740); present value or additional annual revenue per ha from irrigation in the 1st year (NZ$7,159); net present value (NZ41, 764.5) (Table 7.8.3); and longer repayment period (0.92 years), due to its low market value compared to Taewa

(Table 7.8.3). Tutaekuri had an intermediate gross revenue on investment income (NZ$9,043); present value or additional annual revenue per ha from irrigation in 1st year (NZ$7,760); net present value (NZ45, 819.90) (Table 7.8.3); and intermediate repayment period (0.85 years), despite a low marginal yield with irrigation, due to its novel value, partial moisture requirement and low N use. Moreover, the gross revenue for Tutaekuri is expandable by 38% (32 - 44%) with canopy manipulation. However, the repayment period amongst the three productions is within one season for all the production systems. Taewa is more affordable for Maori people and more suitable for environmental sustainability.

The NPV analysis indicates that fully irrigated Moe Moe and partially irrigated Tutaekuri production systems, with low N, would be profitable investments for Taewa growers; due to their high value and low N use (Table 7.8.3). Therefore, growers are not advised to produce Tutaekuri under full irrigation and high N, in addition to Agria under partial irrigation and low N, because these production systems have negative NPV after an initial investment of NZ$6557.36/ha (Table 7.8.3). Taewa, a traditional crop, can be produced economically, whilst supporting water conservation and low N input to the environment in New Zealand.

Table 7.8.3 Investment feasibility analysis for Trail Travel irrigated Taewa and modern potato



Irrigation system and Nitrogen Management for Taewa and modern potato cultivars		Agria 80 kgN/ha	Agria 240 kgN/ha	Moe Moe 80 kgN/ha	Moe Moe 240 kgN/ha	Tutaekuri 80 kgN/ha	Tutaekuri 240 kgN/ha
Average Marketable Yield (t ha^{-1})							
Fully irrigated crop		43	52	33	22	18	10
Partially irrigated crop		34	44	27	16	23	14
Rain-fed crop		32	29	22	14	13	10
Expected price							
Taewa	(NZ$/tonne)						962.00
Agria	NZ$/tonne)						385.00
Additional Gross Revenue (NZ$)							
Fully irrigated crop		4312	8740	10293	7696	4329	770
Partially irrigated crop		539	5583	4329	2309	9043	4137
Added Per ha Costs associated with irrigation & other extra costs							
Fully irrigated crop	(NZ$)			360	1220.70		1580.70
Partially irrigated crop	(NZ$)			150	1133.20		1283.20
Additional Annual Revenue per ha from irrigation in 1st year :							
Fully irrigated crop	(NZ$)	2731.3	7159	8713	6115	2748	-811
Partially irrigated crop	(NZ$)	-744	4299	3046	1026	7760	2853
Net Present Value							
Fully irrigated crop			41,764.50	52,253.40			
Partially irrigated crop						45,819.90	
Pay Back Period in years							
Fully irrigated crop			0.92	0.75			
Partially irrigated crop						0.85	

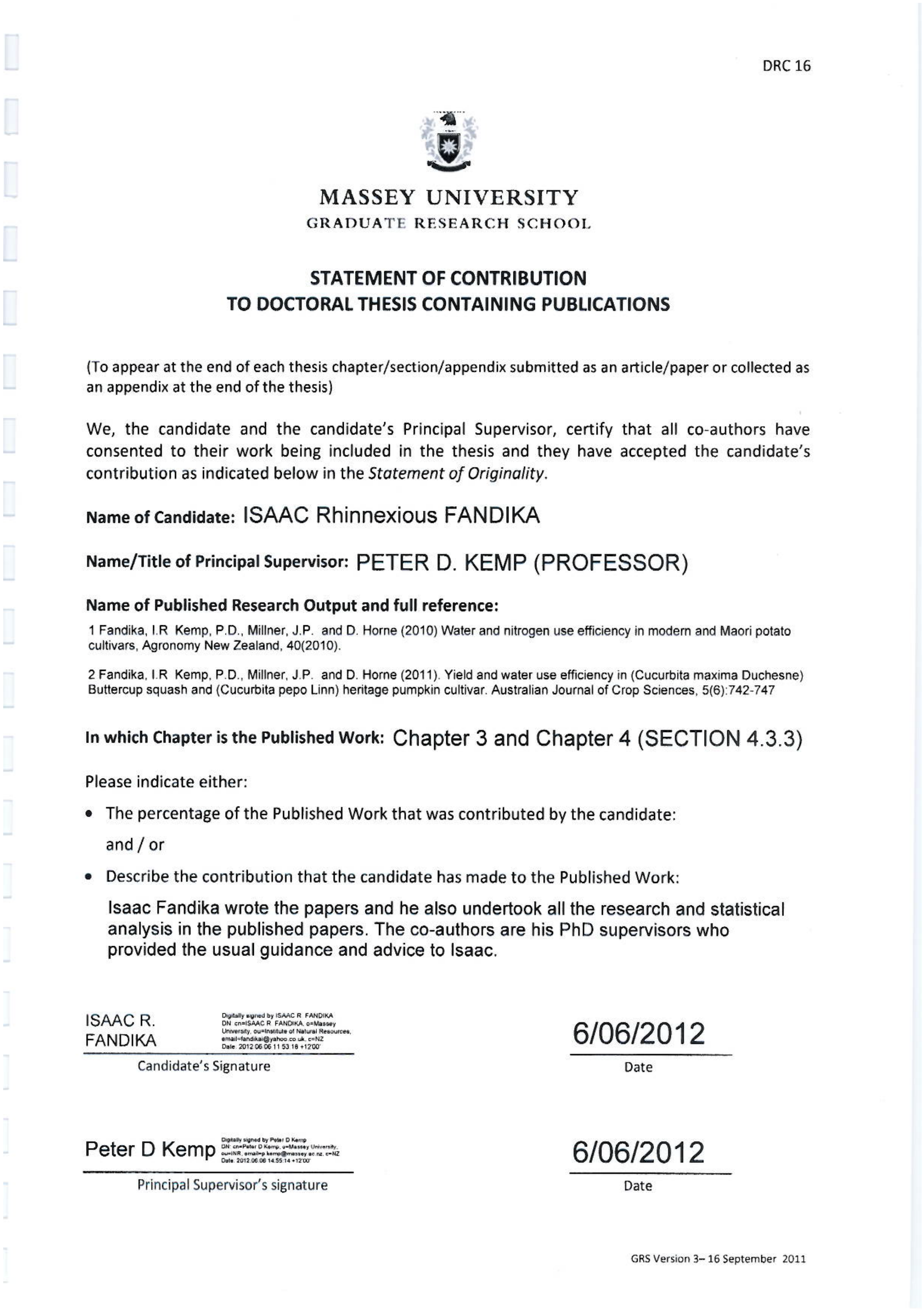
7.8.4 Net present value and pay back for Taewa under Trail Travel irrigator

Year	Mean Yield increase	Additional Gross Revenue	Additional Costs (NZ$)	Net Income (NZ$)	10% Discount	NPV (NZ$)	Cumulative NPV (NZ$)
Agria under full irrigation and 240 kgN ha^{-1}							
						-6557.36	-6557.36
1	22.7	8740	1580.7	7159	1.00	7158.8	601.44
2	22.7	8740	1580.7	7159	0.91	6514.5	7115.9
3	22.7	8740	1580.7	7159	0.83	5941.8	13057.8
4	22.7	8740	1580.7	7159	0.75	5369.1	18426.9
5	22.7	8740	1580.7	7159	0.68	4868.0	23294.8
6	22.7	8740	1580.7	7159	0.62	4438.5	27733.3
7	22.7	8740	1580.7	7159	0.56	4008.9	31742.2
8	22.7	8740	1580.7	7159	0.51	3651.0	35393.2
9	22.7	8740	1580.7	7159	0.47	3364.6	38757.8
10	22.7	8740	1580.7	7159	0.42	3006.7	41764.5
Total						41764.5	
Moe Moe under full irrigation and 80 kgN ha^{-1}							
						-6557.36	-6557.36
1	10.7	10293	1580.7	8713	1.00	8712.7	2155.3
2	10.7	10293	1580.7	8713	0.91	7928.6	10083.9
3	10.7	10293	1580.7	8713	0.83	7231.5	17315.4
4	10.7	10293	1580.7	8713	0.75	6534.5	23850.0
5	10.7	10293	1580.7	8713	0.68	5924.6	29774.6
6	10.7	10293	1580.7	8713	0.62	5401.9	35176.5
7	10.7	10293	1580.7	8713	0.56	4879.1	40055.6
8	10.7	10293	1580.7	8713	0.51	4443.5	44499.1
9	10.7	10293	1580.7	8713	0.47	4095.0	48594.0
10	10.7	10293	1580.7	8713	0.42	3659.3	52253.4
Total						52253.36	
Tutaekuri under partial irrigation and 80kgN ha^{-1}							
						-6557.36	-6557.36
1	9.4	9043	1283.2	7760	1.00	7759.6	1202.2
2	9.4	9043	1283.2	7760	0.91	7061.2	8263.5
3	9.4	9043	1283.2	7760	0.83	6440.5	14703.9
4	9.4	9043	1283.2	7760	0.75	5819.7	20523.6
5	9.4	9043	1283.2	7760	0.68	5276.5	25800.2
6	9.4	9043	1283.2	7760	0.62	4811.0	30611.1
7	9.4	9043	1283.2	7760	0.56	4345.4	34956.5
8	9.4	9043	1283.2	7760	0.51	3957.4	38913.9
9	9.4	9043	1283.2	7760	0.47	3647.0	42560.9
10	9.4	9043	1283.2	7760	0.42	3259.0	45819.9
Total						45819.94	

PUBLICATIONS

1 Fandika, I.R Kemp, P.D., Millner, J.P. and D. Horne (2010) Water and nitrogen use efficiency in modern and Maori potato cultivars, *Agronomy New Zealand*, 40(2010).

2 Fandika, I.R Kemp, P.D., Millner, J.P. and D. Horne (2011). Yield and water use efficiency in (*Cucurbita maxima* Duchesne) Buttercup squash and (*Cucurbita pepo* Linn) heritage pumpkin cultivar. *Australian Journal of Crop Sciences*, 5(6):742-747



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STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: ISAAC Rhinnexious FANDIKA

Name/Title of Principal Supervisor: PETER D. KEMP (PROFESSOR)

Name of Published Research Output and full reference:

1 Fandika, I.R Kemp, P.D., Millner, J.P. and D. Horne (2010) Water and nitrogen use efficiency in modern and Maori potato cultivars, Agronomy New Zealand, 40(2010).

2 Fandika, I.R Kemp, P.D., Millner, J.P. and D. Horne (2011). Yield and water use efficiency in (Cucurbita maxima Duchesne) Buttercup squash and (Cucurbita pepo Linn) heritage pumpkin cultivar. Australian Journal of Crop Sciences, 5(6):742-747

In which Chapter is the Published Work: Chapter 3 and Chapter 4 (SECTION 4.3.3)

Please indicate either:

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- Describe the contribution that the candidate has made to the Published Work:

  Isaac Fandika wrote the papers and he also undertook all the research and statistical analysis in the published papers. The co-authors are his PhD supervisors who provided the usual guidance and advice to Isaac.

ISAAC R. FANDIKA
Digitally signed by ISAAC R FANDIKA
DN cn=ISAAC R FANDIKA, o=Massey University, ou=Institute of Natural Resources, email=fandikai@yahoo.co.uk, c=NZ
Date: 2012.06.06 11:53:18 +12'00'
Candidate's Signature

6/06/2012
Date

Peter D Kemp
Digitally signed by Peter D Kemp
DN: cn=Peter D Kemp, o=Massey University, ou=INR, email=p.kemp@massey.ac.nz, c=NZ
Date: 2012.06.06 14:55:14 +12'00'
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