Chapter 6

Water Footprint Differences of Producing Cultivars of Selected Crops in New Zealand

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Additional information is available at the end of the chapter

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Abstract

Water footprint (WF) is a measure of the amount of water used to produce goods and services. It is a very important concept on indicating how much water can be consumed to complete a process of growing or processing a product at a particular location. However, paucity of water footprint information in countries facing increased competition for water resources between industries limits market access and profit optimization. Water footprint differences of producing selected cultivars of potato, oca and pumpkin squash were determined under irrigation and rain-fed regimes. All crop husbandry practices were followed in potato, oca (3.3 plants m^{-2}) and pumpkin squash (2.2 plants m^{-2}). Water footprint was determined as the ratio of volume of evapotranspiration for irrigated and rain-fed crops plus grey water to total yield. The consumptive water use for the rain-fed crop was 75, 65 and 69% of the irrigated oca, potato and pumpkin squash, respectively, with high water consumption in heritage cultivars. The water footprint was low in pumpkin squash and highest in oca, while potato cultivars were intermediate. Irrigation reduced water footprint especially in crops more responsive to irrigation. Farmers should focus on improving the harvest index and irrigation to reduce water footprint.

Keywords: water footprint, irrigation, potato, oca, pumpkin squash

1. Introduction

The agricultural industry in New Zealand consumes 77% of the freshwater resources [1]. Climate change alongside population and urbanisation has broaden this demand by increasing water utilisation per capita [2]. Water consumption and pollution associated with agriculture has created a great competition for water [3]. As of now groundwater withdrawal and rainwater evaporation, in addition to environmental pollution are accelerating [4]. Until the recent past, there has been little attention to how water is consumed and polluted in agriculture in New Zealand. As a result, the profitability of traditionally irrigated crops reduced [5]. Improved understanding of water footprint (WF) differences in cultivars can reduce the pressure on freshwater, while still maintaining their profits and sustaining the environment. This can be achieved if farmers can start using water sparingly under both modern and heritage crop cultivars [6].

Information on water footprint differences in selected heritage cultivars used by Maori for over 200 years is of significant importance because of their social and cultural value to the economy [7]. McFarlane stated that these heritage cultivars attract a niche market and provide a cultural economy [8]. For instance, the Taewa Maori potato and Kamokamo are a treasured heritage used to enforce land rights, values and sustainable development in New Zealand [9]. Lately, modern crop cultivars have made a significant advancement in productivity, above heritage cultivars. The increased interest in heritage cultivars is restricted by a lack of information on their water use. There is need of information on new ways to grow heritage or modern crops while leaving more water available for people, plants and animals. Idea of considering water use along supply chain can be well explained by the concept of water footprint (WF).

1.1. Definition and significance of water footprint

Water footprint (m^3 ton^{-1}) is defined as the volume of water required to produce a given weight or volume of specific crop [10]. It is a multidimensional indicator showing water consumption volumes by source and polluted volumes by type of pollution where all components of total water footprint are specified geographically and temporally. This footprint is an important factor in future market access, water conservation and growing international trade in agriculture [11]. The study and literature on water footprint expose hidden uses of water resources in producing a crop product over a complete supply chain (producers to consumers). Discovery of such hidden links can form basis for the formulation of new strategies of water governance among growers and consumers. The knowledge of water footprint to final consumers, retailers, food industries and traders in water—intensive products can make them become agent of change in promoting sparing water use. Nevertheless, the water footprint of arable crops has not been sufficiently examined among standard and heritage crop cultivars in New Zealand. In this chapter, we discuss the water footprint differences of producing selected heritage and modern potato, oca and pumpkin squash cultivars grown under rain-fed and irrigated conditions, in New Zealand; and finally what the WF means in the context of the social-economic aspects of growers.

2. Method for assessing the process water footprint of growing selected crops

2.1. Site biophysical characteristics and crop management

Water footprint study of the process of growing crops was conducted at Massey University's Pasture and Crop Research Unit, Palmerston North, between November, 2009 and April, 2011. Massey University is located at a latitude of 40°22′ 54.02 S, longitude 175°36′ 22.80 E, and an altitude of 36 m a.s.l. The soil type is Manawatu sandy loam with Olsen P at 36 mg/L; K at 0.22

mg/100 g, available N at 106 kg ha^{-1} and anaerobically mineralised N kg^{-1} at 76.8 mg at the beginning of the experiment. Climatic data for the site is in **Figure 1**.

The study crops were managed at both supplementary irrigation and rain-fed conditions. There were four cultivars of potato (*Solanum tuberosum* L., *Solanum andigena* Juz & Buk.), two of oca (*Oxalis tuberosa* Mol.) and two of pumpkin squash (*Curcubita pepo* Linn and *Cucurbuta maxima* Duchesne) in each water regime. Rainfall treatment measured green water (rain water) while supplementary irrigation measured both green and blue water footprint (water from river, sea or ocean or ground) [12]. The four-selected potato cultivars included two modern cultivars (Agria and Moonlight (*S. tuberosum* L.)) and two heritage cultivars (Moe Moe (*S. tuberosum* L.) and Tutaekuri (*S. andigena* Juz & Buk.)). The two selected pumpkin squash cultivars included buttercup squash, Ebisu (*C. maxima* Duchesne, a modern cultivar) and Kamokamo (*C. pepo* Linn, a heritage cultivar), while two unnamed oca cultivars with dark orange and scarlet coloured tubers were used.

All crop husbandry practices were followed in potato, oca (3.3 plants m^{-2}) and pumpkin squash (2.2 plants m^{-2}). Potatoes and oca received 12 N:5.2 P:14 K:6 S + 2 Mg + 5 Ca, using 500 kg ha^{-1} Nitrophoska Blue TE at planting, followed by 100 kg N ha^{-1} of urea 21 days later. The pumpkin squash received 12 N:5.2 P:14 K:6 S + 2 Mg + 5 Ca, using 700 kg ha^{-1} Nitrophoska Blue TE at planting, followed by 66 kg N ha^{-1}, when the vines started running. Pests and diseases were also controlled accordingly [13].

2.2. Irrigation and crop water use measurement

In order to measure the actual water use, a soil water balance was used to determine the soil moisture deficit (SMD) on a daily basis during the growth of the crops [14]. The potential evapotranspiration (ETp) in the soil water balance was computed using the FAO 56 Penman-Monteith method [15, 16]. The crop coefficient factors used in the computation were for potato, because this was the most sensitive crop to water use [17]. NIWA/Ag Research in Palmerston North provided daily weather data for running the soil water balance model. The soil water balance model helped to scheduling irrigation centering on refilling 25 mm of the soil moisture deficit when it reaches 30 mm. It was made sure that approximately half the readily available water was supplied. An equation of actual crop evapotranspiration (ET_c) was used as in Eq. (1) [15]. Soil moisture was monitored using time-domain reflectometer (TDR) to determine soil moisture change (ΔS) [13] and surface runoff (R_o) was negligible.

$$ET_c = P + I - D_p - R_o + \Delta S \tag{1}$$

Consumptive 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 [10], as in Eq. (2), where $\sum ETcblue$ and $\sum ETcgreen$ is the accumulation of actual water use (evapotranspiration) over the complete growing cycle for irrigated and rain-fed crops, respectively. Factor of 10 was required to convert water depths of mm into volume in m^3 ha^{-1} [10].

$$\begin{aligned} CWU_{blue+green} &= 10 \times \sum ETcblue + ETcgreen \\ CWUgreen &= 10 \times \sum ETgreen \end{aligned} \tag{2}$$

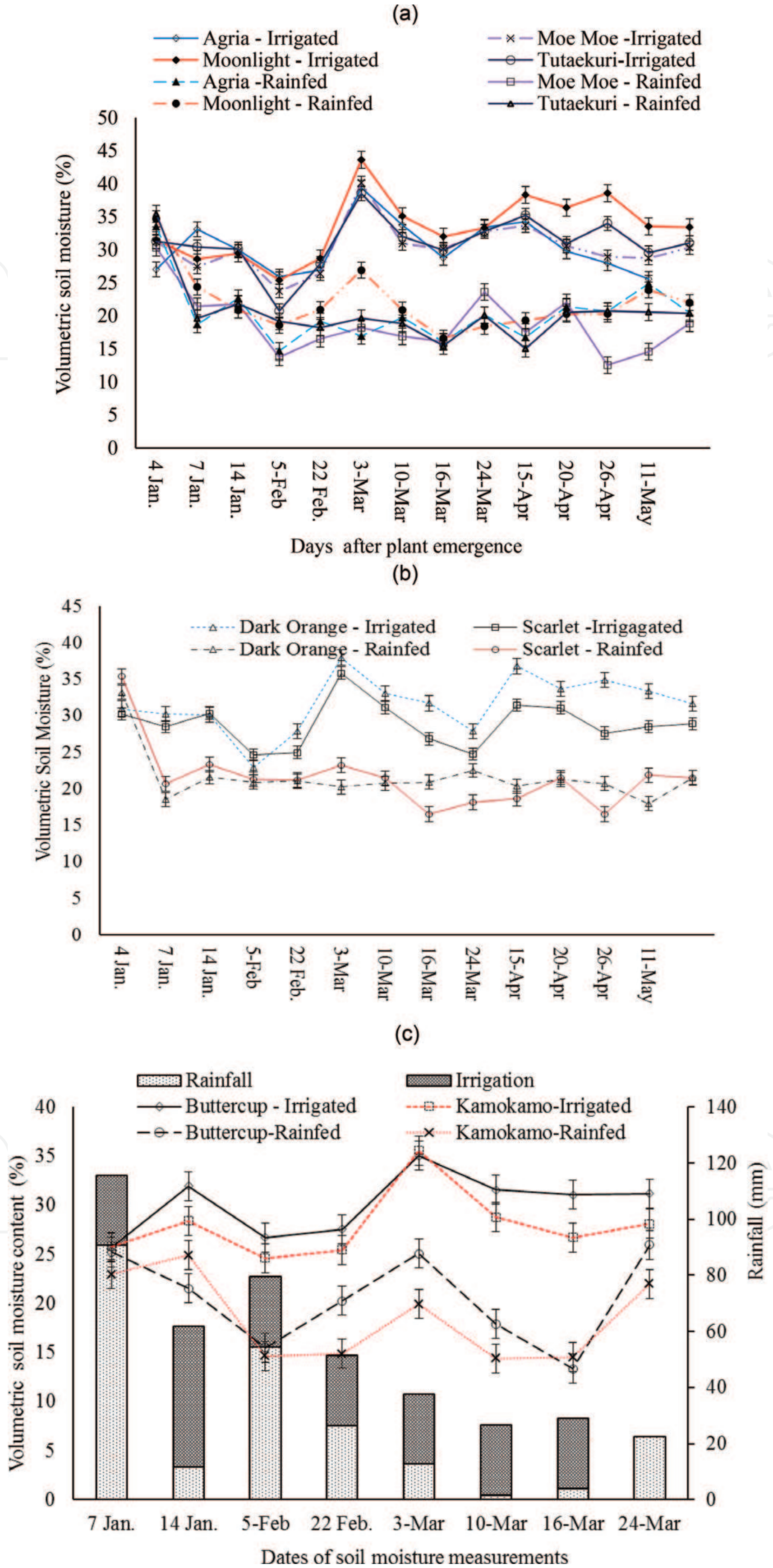

Figure 1. Soil moisture change in heritage and modern potato, oca and pumpkin squash cultivars under irrigation and rain-fed conditions.

2.3. Determination of water footprint differences of cultivars of selected crops

Water footprint (m^3 t ha^{-1}) was determined as the ratio of actual crop water use (m^3 ha^{-1}) to the total yield or total biomass yield (t ha^{-1}) [10]. Total water footprint was the sum of blue, green and grey water footprint. Blue and green water footprint (m^3 t ha^{-1}) was a ratio of blue and green crop water use (mm), to the total yield or total biomass yield (t ha^{-1}), respectively [18]. Grey water footprint (m^3 t ha^{-1}) was determined as a ratio of total volume of water (m^3) required diluting nitrogen that reached the ground water, per ton of produce [19]. Grey water footprint was estimated by multiplying the leaching fraction by the nitrogen application (kg ha^{-1}) and dividing the difference between the permissible limit and the natural concentration of nitrogen in the receiving water body. The study assumed a natural water nitrate concentration of 5.6 mg l^{-1} and the permissible limit of 11.3 mg l^{-1} [20]. Leaching fraction was assumed at 10% [18, 21]. This study compared the water footprint based on actual crop yield and crop water use, in order to remove the disparity of over-estimation, once hypothetical crop and crop water requirements are used [22, 23].

2.4. Social-economic analysis of the selected crop cultivar

An economic assessment of Taewa against modern potato varieties in relation to irrigation investments was done using the net present value (NPV) method. Net present value is an investment analysis also referred as a total of present value of a single project cashflow of the same unit [24]. In order to get NPV, fixed and annual operating costs and expected returns were estimated based on a 5-ha small scale irrigation using a Trail Travel Irrigator to obtain the economic implications of the system on crop production. The data in the study on marketable fresh tuber or marketable fruit yield were used to analyse the economics of Taewa and water footprint. Crop water use and total yield from the three crops were pooled, in order to determine their comparative water footprint differences.

3. Results

3.1. Crop water use and yield summary

Total consumptive water use (blue plus green water) for oca, potato and pumpkin squash in rain-fed and irrigation ranged from 5061 to 6824, 3470 to 5685 and 2551 to 4132 m^3 ha^{-1}, respectively. Consumptive water use (m^3 ha^{-1}) was greatest in oca and lowest in pumpkin squash, while potatoes were intermediate, despite variation within cultivars. The modern and heritage crops differed in their relationship between their maximum water requirement and actual evapotranspiration, thus crop coefficient (k_c) and maturity (**Figure 2**). Taewa and Kamokamo used more water compared to modern cultivars (**Table 1**). Green water was approximately 62, 65, 58 and 70% of consumptive water use, under irrigated modern potato, Taewa, pumpkin squash and oca, respectively. Blue water for oca and potato was 2000 m^3 ha^{-1}, while pumpkin squash received 1750 m^3 ha^{-1}, applied to meet at least 100% of the crop's water requirement.

Grey water also significantly differed between cultivars with the highest in potato and oca. An equivalency of diluting requirement to the grey water for the applied N in potato or oca and

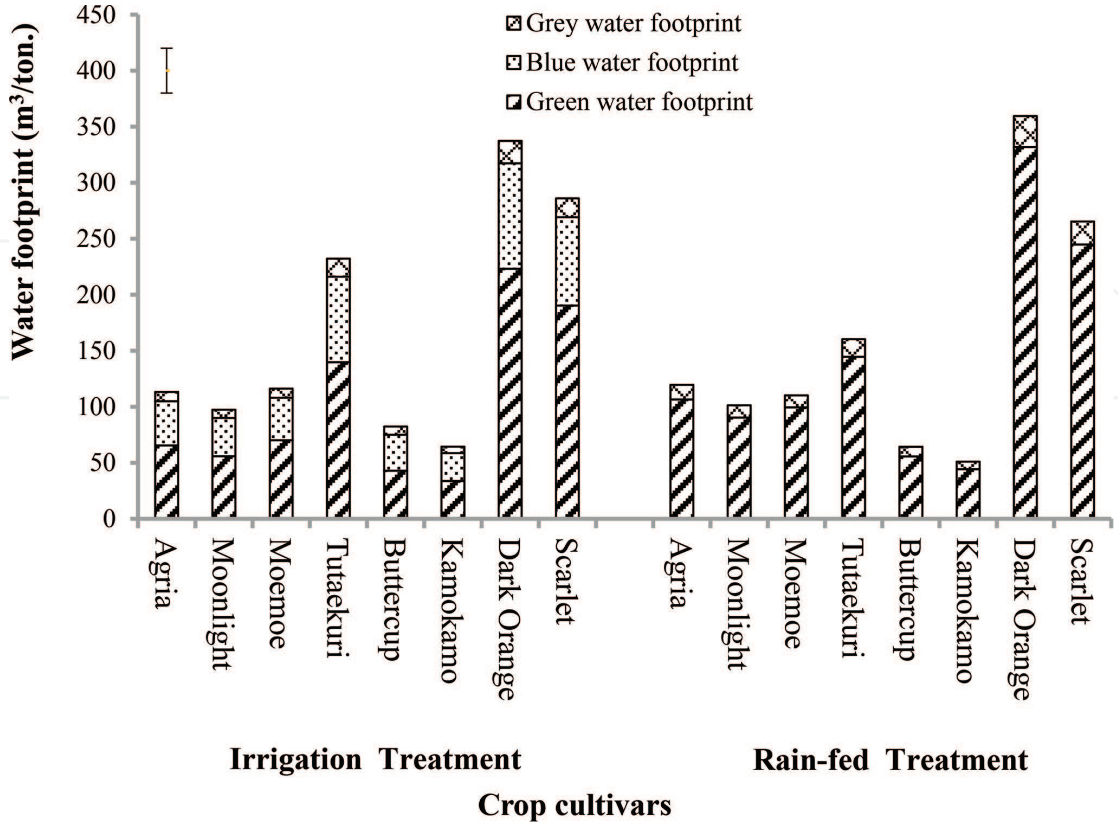

Figure 2. Blue, green and grey water footprint on total yield of potato, oca and pumpkin squash crop cultivars under irrigation and rain-fed condition in New Zealand, 2010. Error bar represents $LSD_{0.05}$.

pumpkin squash was 425 and 398 m^3 ha^{-1}, respectively (**Table 1**). An increase in N rate application raised the grey water in potato and oca compared to pumpkin squash. The actual crop water use for rain-fed crop in oca, potato and pumpkin squash was 74.9, 65.1 and 69% of the irrigated crop, respectively (**Table 1**). The total consumptive water use (m^3 ha^{-1}) was greatest in oca and lowest in pumpkin squash, while potato was intermediate, despite variation within cultivars. Heritage crops (Maori potato, Kamokamo) used more water because of its long growing season.

Differences in yields were observed to be influenced by water regime and crop cultivars among the eight selected crop cultivars. With exception of Tutaekuri, average yields continuously increased from rain-fed (16.7–67.7 t ha^{-1}) to irrigated conditions (23.2–78 t ha^{-1}). Kamokamo had the greatest yields while dark orange had the lowest yields under both water regimes. Average yields for other crops' varieties such as Agria, Moonlight and Moe Moe were similar but greatly lower than Kamokamo. Out of the crop cultivars, oca varieties and Tutaekuri proved to have lowest yield levels. Agria, Moonlight and Moe Moe also demonstrated an ability of partitioning more dry matter to economic yields basing on its harvest index (HI). In summary, the heritage crop cultivars extremely partition more to biomass unlike most of the modern cultivars which partition more to economic yields (**Table 1**).

3.2. Water footprint differences of cultivars of selected heritage and modern crops

3.2.1. Blue, green and grey water footprint on total yield

The green, blue and grey water footprint components varied with both crop cultivars and water regimes as presented in **Tables 2** and **3** and **Figure 2**. The total water footprint of consumptive

Water regime/ cultivars	Planting date	Harvesting date	Total yield (t ha^{-1})	Total biomass (t ha^{-1})	Consumptive water use (m^3 ha^{-1})			Grey water (m^3 ha^{-1})
					Green water	Blue water	Total CWU	
Irrigation								
Agria	10-11-10	17-05-10	51.7	58.7	3326.6	2000	5326.6	424.8
Moonlight	10-11-10	17-05-10	59.4	76.6	3255.6	2000	5255.6	424.8
Moemoe	10-11-10	17-05-10	52.6	76.1	3685.2	2000	5685.2	424.8
Tutaekuri	10-11-10	17-05-10	27.6	54.7	3670.2	2000	5670.2	424.8
Buttercup	09-12-10	29-03-10	54.7	97.7	2325.8	1750	4075.8	398.2
Kamokamo	09-12-10	31-03-10	78.0	149.1	2382.0	1750	4132.0	398.2
Dark O	10-11-10	22-06-10	23.2	55.8	4742.2	2000	6742.2	424.8
Scarlet	10-11-10	22-06-10	25.5	69.5	4824.2	2002	6824.2	424.8
Rain-fed								
Agria	10-11-10	17-05-10	34.0	43.3	3470.6	—	3470.6	424.8
Moonlight	10-11-10	17-05-10	39.7	52.1	3513.0	—	3513.0	424.8
Moemoe	10-11-10	17-05-10	40.1	60.0	3950.0	—	3950.0	424.8
Tutaekuri	10-11-10	17-05-10	30.0	52.8	3933.0	—	3933.0	424.8
Buttercup	09-12-10	29-03-10	47.4	89.6	2551.0	—	2551.0	398.2
Kamokamo	09-12-10	31-0310	67.7	142.7	2603.8	—	2603.8	398.2
Dark O	10-11-10	22-06-10	16.7	42.0	5094.2	—	5094.2	424.8
Scarlet	10-11-10	22-06-10	21.2	50.7	5061.0	—	5061.0	424.8
Significance								
Cultivars			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	—
Water regime			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$LSD_{0.05}$								
Cultivar			10.7	6.23	—	—	—	—
Water regime			5.4	18.9	—	—	—	—

Table 1. Date of planting and harvesting, harvestable yield, total biomass yield and consumptive water use for heritage and modern potato, oca and pumpkin squash crop cultivars in New Zealand, 2010.

water use (blue plus green water footprint or pure green water footprint) of total yield ranges was high in irrigated field and low in rain-fed field (**Table 2**). **Figure 1** evidently show that the blue water footprint in rain-fed crop was zero while the green water footprint of total yield and total biomass yield related to rain-fed environment were high compared to the green water footprint of the irrigated field.

In the irrigated crops, the blue water footprint comprised 27–39% while the grey water footprint made up to 6–9% of the total water footprint of total yield (**Figure 2**). The total water footprint of consumptive water use increased with irrigation in Moe Moe, Tutaekuri, Ebisu, Kamokamo and scarlet oca whilst Agria, Moonlight and dark orange oca decreased total

Water regime/ cultivar	Green water footprint (m^3 ton^{-1})	Blue water footprint (m^3 ton^{-1})	Grey water footprint (m^3 ton^{-1})	Total water footprint (m^3 ton^{-1})
Irrigation				
Agria	65.5	39.4	8.4	113.3
Moonlight	55.8	34.3	7.3	97.4
Moemoe	70.1	38.0	8.1	116.2
Tutaekuri	139.8	76.2	16.2	232.2
Buttercup	42.8	32.2	7.3	82.3
Kamokamo	33.8	24.8	5.7	64.3
Dark orange	223.2	94.1	19.9	337.3
Scarlet	190.3	78.9	16.8	285.9
Rain-fed				
Agria	106.5	—	13.03	119.5
Moonlight	90.4	—	10.92	101.3
Moemoe	99.4	—	10.69	111.1
Tutaekuri	144.6	—	15.62	160.2
Buttercup	55.6	—	8.68	64.3
Kamokamo	44.3	—	6.78	51.1
Dark orange	331.8	—	27.67	359.5
Scarlet	244.8	—	20.55	265.4
Significance				
Cultivars	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Water regime	$p < 0.0001$	$p < 0.0001$	$p < 0.001$	Ns
$LSD_{0.05}$				
Cultivar	44.3	10.7	4.10	54.6
Water regime	15.5	3.7	2.02	27.3

Table 2. Total water footprint of heritage and modern potato, oca and pumpkin squash crop cultivars on total yield basis in New Zealand, 2010.

water footprint of consumptive water use with irrigation (**Table 2**). The dilution requirement for the applied nitrogen in potato, oca and pumpkin squash, had the equivalency of 424.8 and 398.2 m^3 ha^{-1}, grey water footprint, respectively (**Table 1**). The green, blue and grey water footprint reflected the inverse trend observed in total yield and total biomass yield above. All water footprint components above were largest in dark orange oca and smallest in pumpkin squash, Kamokamo (**Figure 2**).

3.2.2. Total water footprint of total yield and total biomass yield

Total water footprint of potato, oca and pumpkin squash on total yield and total biomass yield basis varied with crop cultivars. The total water footprint on total yield basis ranged

Water regime/ cultivar	Green water footprint (m^3 ton^{-1})	Blue water footprint (m^3 ton^{-1})	Grey water footprint (m^3 ton^{-1})	Total water footprint (m^3 ton^{-1})
Irrigation				
Agria	57.5	34.6	7.3	99.4
Moonlight	43.7	26.8	5.7	76.3
Moemoe	48.8	26.5	5.6	80.9
Tutaekuri	68.2	37.2	7.9	113.2
Buttercup	23.8	17.9	4.1	45.9
Kamokamo	16.5	12.1	2.8	31.4
Dark orange	94.6	39.9	8.5	143.0
Scarlet	71.4	29.6	6.3	107.3
Rain-fed				
Agria	82.9	—	10.2	93.1
Moonlight	69.2	—	8.4	77.6
Moemoe	66.5	—	7.1	73.6
Tutaekuri	79.8	—	8.6	88.4
Buttercup	30.2	—	4.7	34.9
Kamokamo	19.7	—	3.0	22.7
Dark orange	141.8	—	11.8	153.6
Scarlet	105.2	—	8.8	114.0
Significance				
Cultivars	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
Water regime	$p < 0.01$	$p < 0.0001$	$p < 0.01$	Ns
$LSD_{0.05}$				
Cultivar	25.57	5.08	2.32	30.48
Water regime	12.78	2.54	1.16	15.24

Table 3. Total water footprint of heritage and modern potato, oca and pumpkin squash crop cultivars on total biomass basis in New Zealand, 2010.

from 64.3 to 337.3 m^3 ton^{-1} under irrigation and from 47.3 to 343.6 m^3 ton^{-1} under rain-fed condition (**Table 2**). The total water footprint on total biomass yield basis was between 31.3 and 143 m^3 ton^{-1} under irrigation, and 22.7 to 153.6 m^3 ton^{-1} under rain-fed (**Table 3**). Regardless of a remarkable crop water use increase with irrigation, the total water footprint on total yield and total biomass yield basis under irrigation and rain-fed regimes were much different.

Figure 3 shows that dark orange oca had the largest average total water footprint of total yield and total biomass while pumpkin squash, Kamokamo had the least. The total water footprint on total yield exceeded total water footprint on total biomass basis in all crop

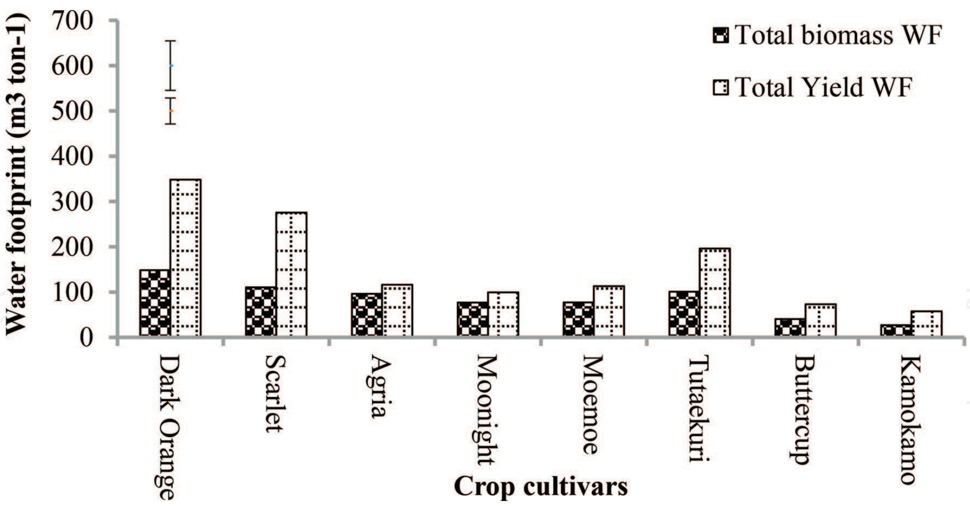

Figure 3. Average water footprint of total yield and total biomass in oca, potato and pumpkin squash cultivars. Error bar represents $LSD_{0.05}$.

cultivars (**Figure 3**, **Tables 2** and **3**). The pumpkin squash cultivars and Moonlight were not much different on total water footprint of total yield but were considerable different to Moe Moe, Agria, Tutaekuri and oca cultivars. Tutaekuri had the greatest total water footprint of total yield and total biomass among potato cultivars though extremely lower to oca cultivars. Nevertheless, the total biomass water footprint for Tutaekuri was not much different from Agria. Moonlight and Moe Moe were second from pumpkin squash in low water footprint of total biomass (**Table 3** and **Figure 3**).

3.3. Social-economic of the selected crop cultivars

Gross revenue on investment income; present value per ha from irrigation in 1st year; net present value was highest in Moe Moe among potato cultivars. Moe Moe also displayed shortest repayment period. The high market value and its intermediary yield response to full irrigation and low N-assisted Moe Moe to have high economic value among the selected potato cultivars. Agria, despite its highest yield response to full irrigation and nitrogen, ended up being the least economic crop enterprise. Agria gross revenue on investment income was NZ$8740; present value per ha from irrigation in the 1st year was NZ$7159; net present value was NZ41,764.5; and its repayment period was longer (0.92 years) than other enterprises. Low market value in Agria compared to Taewa contributed to its lowest economic status. An intermediary economic value was reported in Tutaekuri which had intermediary gross revenue on investment income; present value; net present value and intermediary repayment period. Tutaekuri outperformed modern potatoes in economic terms regardless of its low yield response to irrigation and N just because of its novelty value and reduced water and nitrogen fertiliser requirement.

4. Discussion

4.1. Consumptive water use and yield differences of cultivars of selected crops

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 1** shows how the crop coefficient (or growing stages) overlapped during the growing season between different crops leading to different water use. Application of one irrigation schedule in crops with different kc would result in over-irrigating pumpkin squash. Thus, irrigation scheduling (timing) based on soil water monitoring rather than some approximate modelling approach can significantly improve the water management [25], that is, the total water footprint. Differences in growth stages and date to maturity might contribute to great differences in crop water requirement and water footprint among the selected crops cultivars [15]. From the study, it is definite that Taewa and oca have the longest duration of growth to maturity compared to the other selected crop cultivars [13].

Most of heritage crop cultivars used more water than modern cultivars. Likely, the large biomass and longer growth cycle in heritage crop cultivars (Kamokamo, Tutaekuri, oca and Moe Moe) made them use more water than modern cultivars. This study considered actual evapotranspiration and other discharges in determining the water footprint, as suggested by Maes [23]. In this case, the water requirement was not equal to the actual total consumptive water use, thus remedying the over-estimation. This is in contrast to water footprint determination in other studies, where hypothetical crop yield and evapotranspiration were used [26]. Apart from, expected enormous variability in crop water use within the area in future, the current results provide a great benchmark of heritage and modern crop water requirement and water footprint for the studied area.

4.2. Water footprint differences of cultivars of selected heritage and modern potato, pumpkin squash and oca

Water footprint components differ with crop type or cultivars and water regimes as also reported in energy crops [27]. Pumpkin squash, Kamokamo, was the most efficient crop cultivar, while dark orange oca was the least efficient crop. Equivalency in water footprint could be noticed between pumpkin squash cultivar and Moonlight. Nevertheless, both were five times slighter than water footprint of oca. Likewise, Moonlight, Agria and Moe Moe equaled in water footprint. Tutaekuri has largest water footprint almost double that of other potato cultivars. There more benefits to grow Tutaekuri and pumpkin squash cultivars under rainfed than under irrigated conditions. If not, there is no gain in growing oca under irrigation, excluding in the case of a likely premium price, which would offset low water productivity, compared to potato and pumpkin squash.

The average water footprint of growing potato reported in this study (ranging from 46 m^3 ton^{-1} to 335 m^3 ton^{-1}) were greater than that for the Netherlands and almost equal to USA and Brazil, except for Tutaekuri, which was equal to the water footprint of growing potato in Zimbabwe [27]. The water footprint of 72 m^3 ton^{-1} was reported in Netherlands, 111 m^3 ton^{-1} in USA, 106 m^3 ton^{-1} in Brazil and 225 m^3 ton^{-1} in Zimbabwe [27] for producing potatoes. Besides, our study demonstrates that water footprint of growing potato and pumpkin squash in New Zealand is either average, or smaller than that of crops with smallest water footprint in referred regions. Oca was found to have largest total water footprint. However, oca average water footprint in this study is within the range of smallest water footprint reported in Netherlands, USA, Brazil and Zimbabwe among sugar beet, sugarcane and maize [27].

An average of 12, 10, 11, 20, 7, 5, 35 and 28 l of water (in virtual water content form) would be required to produce 100 g of Agria, Moonlight, Moe Moe, Tutaekuri, Buttercup squash, Kamokamo, dark orange and scarlet oca, respectively. Efficient crop water management and crop cultivar choice might contribute to lower virtual water content of producing potato and pumpkin squash than 25 l/100 g for potato tuber [28] and 23.8 l/100 g for pumpkin [22], which were reported as average global and Indian virtual water content, respectively. On the other hand, oca virtual water content is still falling outside the 25 l/100 g for potato tuber. These disparities in water footprint are within or above those reported in the 1995–2006 global water footprint of pumpkin squash (336 m^3 ton^{-1}) and potato (287 m^3 ton^{-1}) [12].

The results suggest that there are great disparities in virtual water content and water footprint within global averages, which may be due to climate, cultivars and methodological differences, when estimating crop water use [22, 28]. This study used actual water use and actual yield, as suggested by Maes [22], while the study referred to used hypothetical crop yields and water use [26]. On the other hand, the virtual water content and water footprint in this study, outweigh the global water footprint put forward by Mekonnen [12]. The reason for such disparities with this study is that most referred global water footprint studies theoretically estimated crop water use while this study practically recorded the actual water used. The theoretically estimated water use might have been over-estimated while our study might sparely use the water resulting into lower water footprint. It is globally agreed that smart and efficient practices in agriculture, selection of efficient crop cultivars in water use and good weather patterns do assist in reducing water footprint of producing various crops.

Irrigation increases total water use compared to rain-fed agriculture. In this study blue water raised total crop water use by 34, 48 and 59%, in oca, potato and pumpkin squash cultivars, respectively. Consequently, blue water clearly increased the total water footprint. Total water footprint increased by 5, 45, 28, 25 and 8% in irrigated Moe Moe, Tutaekuri, Buttercup squash, Kamokamo and Scarlet oca. However, irrigation reduced total water footprint in Agria, Moonlight and dark orange oca by 6, 4 and 7%. The earlier trends were reported in wheat whereas the later was reported in sugarcane and soybean, respectively [12]. For crop varieties which positively respond to irrigation, the intervention is indispensable to reduce the total water footprint, by improving the economic yields. Nevertheless, this is contrary to like Moe Moe, Tutaekuri, Buttercup squash, Kamokamo and scarlet because the intervention raised the actual evapotranspiration nearly to potential evapotranspiration resulting into reduced water footprint, even with improved yield. The findings emphasise that irrigation is very important for crop yield quality and yield enhancement as well as reduced water footprint where rainfall is limited. Apart from differences in water footprint influenced by crop varieties and differences and crops, water footprint also extensively differ in their water footprint at different irrigation management.

Irrigation scheduling method would influence the water footprint of producing various crops—however, this is dependent on crop cultivars. Partial irrigation reduced water footprint in Tutaekuri while full irrigation reduced water footprint in Moe Moe and Agria. The differences about crop varieties response to different irrigation schedules are very significant because they indicate disparity of water use among crop varieties. This result is very useful in selection for crop varieties that are sparing in water use or drought tolerant and breeding for water use efficiency.

Hedley proved that the water footprint of modern potato production is slighter small than that of maize and pasture [29]. Hedley report registered water footprint of 308 and 325 m^3 ton^{-1}

in potato 622 and 654 m^3 ton^{-1} in maize and 2651 and 2667 m^3 ton^{-1} in pasture at varied rate irrigation and uniform rate irrigation, respectively. It is noted that the total water footprint of growing potato by Hedley et al. [29, 30], was higher than those reported by Hoekstra [31] and the water footprint for this study, except for Tutaekuri. Similarly, the study under this report vividly shows that water footprint differed between full irrigation and rain-fed that ranged from 95 to 111 m^3 ton^{-1} (modern potato); 110–220 m^3 ton^{-1} (Taewa) in 2009/2010. In 2010/2011 the water footprint for water regimes ranged from 163 to 586 m^3 ton^{-1} (full irrigation), 173–406 m^3 ton^{-1} (partial irrigation) and 198–505 m^3 ton^{-1} (rain-fed). The lowest water footprint was found in Agria and the highest in Tutaekuri. From this discussion and **Figure 3**, it is well illustrated that water management within different crop cultivars influences levels of water footprint. Apart from differences in water footprint caused by varieties differences, water footprint may also extensively differ in their water footprint due to pests' infestation. Farmers need to keep fields weed free to reduce pests and diseases incidences.

Pests and diseases affect water footprint of producing selected crop cultivars because they reduce yields without affecting water input. In case of this study, water footprint of Taewa between seasons differed due to pests' infestation. As weather variations between seasons Water footprint was greatly higher in 2011 than in 2010 (**Figure 3**). Potato psyllid infestation influenced the increase in water footprint in 2011. However, the water footprint of producing potato without psyllid infestation, in 2009/2010, was smaller than the global water footprint (160 m^3 ton^{-1}) for producing potato. Potato infested with psyllid in 2010/2011 behaved differently, only a well-managed full irrigation regime of modern potato and Moe Moe, obtained a water footprint approaching the global water footprint of 160 m^3 ton^{-1}. A combination of proper management of irrigation under pests' infestation can help to reduce water footprint.

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 [22, 28]. However, the water footprint for crops grown in New Zealand can be reduced through good management [12]. 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 [26]. 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.

4.3. Social-economics of the selected crop cultivars

A premium that farmers get at market on crop cultivar has higher influence on smallholder farmer's social-economic status than sole yield and sole irrigation response factors. In our case, fully irrigated Moe Moe and partially irrigated Tutaekuri production systems, were economically viable due to their high value at market. The novel value of most heritage crops are value which have been based on social preferences based on their superiority flavour, texture and colour. Fully irrigated Moe Moe and partially irrigated Tutaekuri production systems, with low N, would be profitable investments for Taewa growers because they have high value and low N use. For growers to maintain these economic benefits they should be advised to produce Tutaekuri under partial irrigation and low high N, and Moe Moe under full irrigation with low N. It is not advisable for growers to produce Agria under partial irrigation and low N, because this production system has negative NPV. Economic water productivity is expected to be high in Taewa because of the premiums at market. Premiums, socially and economically forces production of Taewa among the highest producer but low valued. It is evidenced that issue of water footprint requires financial attachment to attract farmers.

5. Conclusion and recommendations

In the field, water regimes differently influence crop production and the value of water footprint for both heritage and modern crop cultivars, depending on the crop water use characteristics and field management. Pumpkin squash, Kamokamo, has a low water footprint, since it genetically uses water more sparingly, compared to all the other crop cultivars studied. In spite of this, the yield response to irrigation is highest in modern potato, while Kamokamo is comparable to Moe Moe and Buttercup squash and dark orange oca. It can be concluded that pumpkin squash requires only a small amount of water, in order to produce total fruit yield compared to potatoes and oca. Potatoes, except Tutaekuri, are more responsive to irrigation compared to pumpkin squash and oca. The yields and water footprint of heritage potato is greatly affected by cultivars used and water regimes, unlike the case of oca. It can be concluded that there are water footprint differences between cultivars of different crops and within crops in New Zealand. Knowledge of these water footprint differences can assist growers to manage their crops and water resources sparingly. It is therefore recommended that growers should be properly selecting crops and crop varieties according to their water availability, market price, properly schedule irrigation and nitrogen application as well as pests and disease control in order to reduce water footprint of growing their crops at field level.

It is recommended that farmers should strive to reduce water footprint either by avoidance of using two much of other inputs or by replacement of inefficient technologies by very efficient technologies as detailed below:

1. Farmers should be advised to strive to reduce grey water footprint in their fields. Grey water footprint would be decreased if application of chemical fertilisers, pesticides and herbicides to the field is avoided or reduced or by following efficient ways of using fertilisers as well as applying better application techniques or use of organic fertilisers and proper timing of fertiliser and irrigation application.

2. Farmers should also be advised to decrease green water footprint and blue water footprint. The green and blue water footprints would be greatly lessened by enhancing green and blue water productivity. Our study indicates that application of less water through smart irrigation scheduling (replacing full irrigation by partial irrigation) and selection of water efficient crop cultivars (replacing heavy water users by efficient water users) would help to maximise water productivity (striving for higher yield per cubic of water used for production) thereby reducing both green and blue water footprint.

3. Agricultural Extension Officers need to be guided to assist farmers in defining their target of best agricultural technology practices for reducing water footprint and formulating targets to be achieved in order to contribute to reduction of water footprint. Where possible farmers should be assisted to monitor and measure their water footprint in their environment. This can be achieved by setting environmental and social safeguards plan that would help to reduce risk of water footprint by investing in reasonable water use, better-quality catchment water management and sustainable water use.
4. Governments should formulate policies that include goal of sustainable usage of water resources. The policies should promote smart agriculture: that is, efficient irrigation (drip irrigation), conservation agriculture, system of rice intensification (SRI), crops that are efficient in water use and organic fertilisers.

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