THE ORCHARD WATER FOOTPRINT OF NEW ZEALAND KIWIFRUIT – UPSCALING FROM THE ORCHARD TO THE COUNTRY

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Introduction

Globally, water resources are scarce, with industry, a fast growing urban population, and agriculture competing for it. Currently, irrigation for primary production is the world's largest user of fresh water. About 66% of all water withdrawn for direct human activities is being used for agriculture (Scanlon et al., 2007). In New Zealand, some 77% of allocated water is for irrigation (MfE, 2006). Currently, about 1.2 billion people worldwide live in river basins that are already characterized by physical water scarcity (Molden et al., 2007). Without major changes in land and water productivity, agricultural water demand is predicted to increase by a further 70-90% (De Fraiture and Wichelns, 2010). Additionally, irrigated agriculture can have an adverse impact on the environment. For example, agricultural water management has led to a modification of river flow patterns, and downstream wetlands or coastal ecosystems (Agardy and Alder, 2005; Finlayson and D'Cruz, 2005). Also, the nutrient enriched leachates from agricultural fields can compromise receiving- water quality and cause eutrophication and hypoxia in nearby rivers, lakes, and even the near-shore ocean (Diaz, 2001).

Hydrologists have identified various strategies for solving the problems of water scarcity and water quality associated with irrigation (De Fraiture and Wichelns, 2010). Traditionally, they focus their efforts mainly on the agricultural producers and the technical aspects of irrigation and drainage, rather than convincing the consumers to choose those agricultural products that have no or less adverse impacts on freshwater resources. Only recently, international trade and a change in consumers' attitudes were discussed as viable tools for a more sustainable use of freshwater. For example, in the four scenarios of possible global futures used by the Millenium Ecosystem Assessment, meat consumption varied from about 40 to 70 kg per person and year. In the high meat consumption scenario about 15% more water would be consumed compared to the high vegetable consumption one (Alcamo et al., 2005). But the lack of a generally accepted methodology for quantifying the influence of products on water scarcity and water quality that could inform markets and consumers currently impedes further progress for using international trade as a tool to address the global problem of the scarcity and quality of freshwater resources.

Water footprints have been proposed as being suitable indicators for quantifying the impact of goods and services on freshwater scarcity and quality. Thus far, the discussion around the definition and application of water footprints has been led mainly by economists and life-cycle analysts (Hoekstra, 2009; Ridoutt et al., 2009). They have assessed the water footprints of various agricultural products, and they have been mooted as a decision support tool for supermarkets to help with the question as to which country a particular agricultural product should be sourced from (Mila i Canals et al., 2010; Mila i Canals et al., 2009).

The use of water footprints has even prompted the International Standardization Organization (ISO) to begin to develop an internationally acceptable methodology. This process is still at an early stage, and hydrologists still have the opportunity to discuss the merit of different concepts of water footprints and, if necessary contribute to their formulation. The objective of this paper to participate in this discussion and use the example of one of New Zealand's most important export products, kiwifruit, to consider the merits and drawbacks of different approaches to assess the water footprint of products

Our paper has two goals:

1. To define and quantify a set of hydrological criteria for assessing the impact of NZ kiwifruit production on freshwater resources.
2. To evaluate and discuss the performance of two different concepts of water footprints for representing the impact of the production of NZ kiwifruit on local freshwater resources.

Methods

The impact of New Zealand kiwifruit on freshwater resources

We first follow the approach of others (Mila i Canals et al., 2010; Mila i Canals et al., 2009) who suggested in the context of a product life cycle assessment (LCA) that two types of impacts on freshwater resources need to be considered. This is firstly the overexploitation of freshwater resources, and secondly the impact on freshwater ecosystems. For our study, and in the context of kiwifruit production in New Zealand, we have interpreted and defined the impact on freshwater ecosystems to mean the deterioration of the quality of freshwater resources. For convenience, we term these two aspects as being the impact on water scarcity and quality.

Impact on water scarcity

In New Zealand, the water for kiwifruit production is extracted either by roots of the vine, or by irrigation pumps from aquifers underneath the orchard. The majority of kiwifruit orchards are located on floodplains of well-drained soils for kiwifruit are intolerant of impeded drainage conditions. For our study we have assumed that water originating from irrigation or rainfall within the orchard, is either taken up by the roots of kiwifruit vines or by the groundcover vegetation of the inter-row, or it directly, or indirectly, drains back into the underlying aquifer.

In New Zealand, kiwifruit are usually harvested in April, and the kiwifruit industry, therefore, defines a 'year' as the annual period from April to April. We have therefore adopted this definition of a year, instead of a hydrological year.

The water mass balance for a year for a typical New Zealand kiwifruit orchard system can be described by:

$$\Delta S + \Delta GW = RF^{*} - ET^{r}_{c} - \Delta ET^{r,i}_{c}, \qquad \textbf{(1)}$$

where ΔS [mm/year] is the net change in the soil water storage, ΔGW [mm/year] is the net flux of groundwater into or out of the aquifer directly below the orchard area, RF^{*} [mm/year] is the effective rain throughfall (rainfall minus any interception by the kiwifruit vines or groundcover vegetation), ET^r_c [mm/year] is the evapotranspiration losses from a rainfed orchard (no irrigation), ET^i_c [mm/year] is the evapotranspiration losses from an irrigated orchard, and $\Delta ET^{r,i}_c$ is the difference between the latter two. The detailed definitions of ΔS and ΔGW are given below in equation 2 and 3, respectively.

In our context, we have assumed that steady-state groundwater flow occurs under the area of a kiwifruit orchard. Equation (1) indicates that the kiwifruit production can have an impact on the scarcity of water in two freshwater stores, namely the storage of water in the soil, and in the groundwater.

In the formulation of equation (1), and of the following equations we have deliberately separated two different sources of water for plants, rainfall or irrigation, for the hydrological processes, as this separation is at the core of the water footprint concept. The net change of the soil water store, ΔS, can be described as:

$$\Delta S = RF^{*} + IR - D^r - \Delta D^{r,i} - ET^r_{c,s} - \Delta ET^{r,i}_c - RO^r - \Delta RO^{r,i} \,, \qquad \textbf{(2)}$$

where D^r [mm/year] is the drainage out of the rootzone in a rainfed orchard, D^i [mm/year] is the same but for an irrigated orchard, $\Delta D^{r,i}$ [mm/year] is the difference between D^r and D^i, RO^r [mm/year] is the run-off in a rainfed orchard, RO^i [mm/year] is the same but for an irrigated orchard, $\Delta RO^{r,i}$ [mm/year] is the difference between the RO^r and RO^i, and IR [mm/year] is the annual amount irrigation used.

It follows that ΔS is negative, when the net loss of water from the soil is larger than the net gain of water by rainfall and irrigation, and vice versa.

The net change of the aquifer freshwater store directly below the orchard area, ΔGW, can be calculated as:

$$\Delta GW = -IR + D^r + \Delta D^{r,i} + RO^r + \Delta RO^{r,i}. \qquad \textbf{(3)}$$

Now by adding the two sub-systems for freshwater storage, ΔS and ΔGW (Equations (2) and (3)), together, we obtain the complete water mass balance as presented in Equation (1).

It follows that ΔGW is negative, when the extraction of water from the aquifer for irrigation is larger than the return-flow of water by drainage and run-off. Conversely, a positive value of ΔGW would indicate that kiwifruit production as a land-use has contributed to groundwater recharge.

Impact on water quality

In the context of water quality we only consider the transfer of pollutants from the rootzone soil of kiwifruit orchards, through the vadose zone, to the groundwater. According to the mechanistic simulations we have carried out, nitrate-nitrogen (NO_3-N) is the dominant pollutant in the leachate leaving the root zone of New Zealand kiwifruit orchards. The concentrations and loads of other pollutants, such as pesticides were calculated to be negligibly small, and their concentrations were even below the detection limit of currently available analytical methods.

The impact of pollutants on groundwater quality can either be quantified by a concentration (mg/l), or as the total load when the leachate concentration is multiplied by the drainage volume (kg/ ha and year). For the scope of this paper we reference five different NO_3-N concentrations in the groundwater.

- 0.0 mg/l NO_3-N. About 8% of New Zealand's aquifers that were sampled in 1995-2006 in the New Zealand National Groundwater Monitoring Programme had nitrate concentrations below the detection limit and we assumed this to mean 0.0 mg/l (Anonymous, 2007). This value we therefore term the 'concentration of pristine groundwater'. We have used this value as one of the options when considering the natural background concentration.

- 1.3 mg/l NO_3-N. About 50% of New Zealand's aquifers that were sampled between 1995 and 2006 by the New Zealand National Groundwater Monitoring Programme had nitrate concentrations up to 1.3 mg/l (Anonymous, 2007). This value we term the 'average groundwater' concentration in New Zealand. We have used this as an alternative value for selecting a value for the natural background concentration.

- 3.5 mg/l NO_3-N. An analysis based on the New Zealand National Groundwater Monitoring Programme suggested a value of 3.5 mg/l NO_3-N can be used as an "almost certain indicator of human influence" (Daughney and Reeves, 2005). This value we have therefore termed indicator of human influence in groundwater.

- 7.2 mg/l NO_3-N. This is the trigger value (TV) for ecosystem protection suggested by the Australian and New Zealand Environment Conservation Council (ANZECC) guidelines for groundwater investigations, and so we have termed it the TV for ecosystem protection of groundwater systems.

- 11.3 mg/l NO_3-N. This value is the NZ Ministry of Health's drinking water standard. We refer to this as the concentration of the drinking water standard in New Zealand.

Water footprints as indicators for the impact on water scarcity and quality

We have adopted two approaches for defining the green and blue-water footprints. For simplicity, these will be termed Approaches 1 and 2. Approach 2 is that which is currently recommended by the WFN (Hoekstra et al., 2009).

Representation of ΔS in the green-water footprint

The WFN defines the green water as "the precipitation on land that does not run-off or recharge the groundwater but is stored in the soil" (Hoekstra et al., 2009). The net change in the green water, $\Delta\Gamma$ [mm/year], is given by:

$$\Delta\Gamma = D^r + ET^r_c + RO^r - RF^* \qquad \textbf{(4a)}$$

The WFN focuses on the green-water consumption ΓC [mm/year] that they define as "the volume of rainwater consumed during the production process" (Hoekstra et al., 2009) which can be written as:

$$\Gamma C = ET^r_c \qquad \textbf{(4b)}$$

We assessed mathematically how closely $\Delta\Gamma$ and ΓC represent the hydrological term of ΔS by shading the terms that are different from ΔS in grey. The relation of $\Delta\Gamma$ and ΔS is given by:

$$\Delta\Gamma = -\Delta S + IR - \Delta D^{r,i} - \Delta ET^{r,i}_{c} - \Delta RO^{r,i} \qquad \textbf{(5a)}$$

Note, that $\Delta\Gamma$ is equivalent to $-\Delta S$ when no irrigation is used. The relation of ΓC and ΔS is given by:

$$\Gamma C = -\Delta S + IR + RF^{*} - D^{r} - \Delta D^{r,i} - \Delta ET^{r,i}_{c} - RO^{r} - \Delta RO^{r,i} \qquad \textbf{(5b)}$$

Both $\Delta\Gamma$ and ΓC can be used to define a green-water footprint (green WFP) [l/TE] by relating them to the kiwifruit productivity. The functional unit of productivity in the New Zealand kiwifruit industry is the tray equivalent, TE, which is defined as 3.6 kg of fresh weight of ZESPRI® green kiwifruit.

The *green* WFP^1 using Equation 4a, namely our proposed Approach 1, is given by:

$$Green\ WFP^{1} = [(\Delta\Gamma \times 10)/FW] \times W_{TE}, \qquad \textbf{(6)}$$

where the superscript '1' indicates that Approach 1 (Equation 4a) has been used for the calculation. The other variables are the yield fresh weight of export-quality Class 1 kiwifruit per ha, FW [t/ha], and where W_{TE} [kg/TE] is the fresh weight of kiwifruit in a tray equivalent (=3.6 kg). The factor 10 is for unit conversion.

The *green* WFP^2 of the WFN using Equation 4b , namely Approach 2, is given by:

$$Green\ WFP^{2} = [(\Gamma C \times 10)/FW] \times W_{TE}, \qquad \textbf{(7)}$$

where the superscript '2' indicates that approach 2 (equation 4b) has been used for the calculation.

We will discuss later, the implications of these different approaches.

Representation of ΔGW by the blue-water footprint

The WFN has defined blue water as "fresh surface and groundwater, i.e. the water in freshwater lakes, rivers and aquifers" (Hoekstra et al., 2009). We have adopted the same definition for our study. We have defined the net change in the blue water stocks, ΔB [mm/year], to be the same as $-\Delta GW$ because we are considering the groundwater resources immediately below the kiwifruit orchard (see Equation (3)). The WFN have defined a blue water consumption BC [mm/year] as being "the volume of surface and groundwater consumed as a result of the production" (Hoekstra et al., 2009) which they recommend to be calculated from:

$$BC = \Delta ET^{r,i}_{c} \qquad \textbf{(8)}$$

Note that this definition implies that in a rainfed system there is no blue water consumption. But we consider the local hydrology of the orchard, and so have assumed that all irrigation water that is not stored in the soil or lost by evapotranspiration actually does return to the aquifer under the orchard, that is some part of it replenishes the same blue water resource from which it was originally extracted from.

We assessed mathematically how closely ΔB and BC represent ΔGW by shading the terms that are different from ΔGW in grey. The change in blue water, ΔB**,** is identical to $-\Delta GW$**,** and is in a mathematical sense a perfect inverse representation. The relation of BC and ΔGW is given by:

$$BC = -\Delta GW - IR + D^r + \Delta D^{r,i} + RO^r + \Delta RO^{r,I} + \Delta ET^{r,i}{}_c \qquad \textbf{(9)}$$

Both ΔB and BC can be used to define a blue-water product footprint (blue WFP) [l/TE] by relating them to kiwifruit productivity.

The *blue* WFP^1 using $\Delta B = -\Delta GW$ is our Approach 1 and it is given by:

$$Blue\ WFP^1 = [(\Delta B \times 10)/FW] \times W_{TE,} \qquad \textbf{(10)}$$

where the superscript ‘1’ indicates that the relation of $\Delta B = -\Delta GW$ of our Approach 1 has been used for the calculation.

The *blue* WFP^2 using Equation 8 is that of the WFN’s Approach 2 and it is given by:

$$Blue\ WFP^2 = [(BC \times 10)/FW] \times W_{TE,} \qquad \textbf{(11)}$$

where the superscript ‘2’ indicates that approach 2 (equation 8) has been used for the calculation.

We will discuss later the implications of these two approaches.

Grey water footprints as indicators for the impact on water quality

For the grey water footprint we do not propose a new method, rather we follow the definition of the WFN. The WFN defines grey water as “the water required to dilute pollutants to such an extent that the quality of the water remains above agreed water quality standards” (Hoekstra et al., 2009). Accordingly, the grey water dilution GD [mm/year] is calculated as:

$$GD = (D^r + \Delta D^{r,i}) \times [(C-C_b)/(C_{max}-C_b)], \qquad \textbf{(12)}$$

where C [mg/l] is the average concentration of the leachate of most environmental concern over the time period considered, C_b [mg/l] is the natural background concentration of this chemical, and C_{max} is the concentration of the water-quality criterion being used. The grey water dilution is then transferred into a grey-water product footprint, *grey WFP* [l/TE] by:

$$Grey\ WFP = [(GD \times 10)/FW] \times W_{TE} \qquad \textbf{\textit{(13)}}$$

The productivity, climate, soils, and irrigation management of the major kiwifruit growing areas in New Zealand

In New Zealand more than 80% of ZESPRI® Green kiwifruit are harvested in the Bay of Plenty (BOP) region, in the areas around the cities of Katikati, Tauranga, Te Puke, and Whakatane (Table 1). In kiwifruit orchards across the BOP region, the effective rainfall is significantly larger than the evapotranspiration (Fig. 1). The soils are free-draining Andisols and can typically store more than 400 mm (Table. 1), so that there are large amounts of plant-available water. Irrigation is thus used in only about 30% of the kiwifruit orchards in this area (Table 1). In comparison, the kiwifruit-growing regions of Gisborne, Nelson, and the Hawke's Bay region are much drier, with little difference between effective rainfall and evapotranspiration (Fig. 1). However, these three drier regions only contribute about 8% of the national harvest of ZESPRI® Green kiwifruit, although 90% of the kiwifruit orchards in these areas do use irrigation (Table 1). The yield of ZESPRI® Green kiwifruit in New Zealand typically ranges between 4000-8000 TE/ha, which is equivalent to 14.4 – 28.8 t/ha of fresh fruit weight.

Table 1: The productivity (ZESPRI® Green), key soil hydraulic properties, and irrigation management of the major kiwifruit growing areas in New Zealand. For the key soil properties the mean and in brackets the standard deviations are given.

Area	Productivity[1]	Soil hydraulic characteristics[2]		Irrigation management[3]			
	Fraction of total harvest in 2008/09	FC[4]	PAW[5]	Fraction 'Rainfed'	Fraction 'Efficient'	Fraction 'Over- '	Fraction 'Over-plus frost- '
	%	mm	mm	%	%	%	%
Northland	2.5	920 (202)	246 (111)	10	50	20	20
Auckland	5.1	887 (55)	315 (85)	20	40	20	20
Katikati	14	909 (150)	444 (91)	70	10	10	10
Tauranga	15.5	909 (150)	444 (91)	70	10	10	10
Te Puke	48.3	909 (150)	444 (91)	70	10	10	10
Whakatane	4.6	909 (150)	444 (91)	70	10	10	10
Waikato	2.2	950 (122)	378 (127)	40	20	20	20
Gisborne	1.3	807 (177)	495 (211)	10	30	30	30
Hawke's Bay	0.9	712 (131)	485 (36)	10	30	30	30
Nelson	5.6	662 (246)	305 (126)	10	30	30	30

[1]: The fractions were derived from the ZESPRI® 2008/09 Annual report, and they relate to the ZESPRI® Green variety (ZESPRI, 2009).
[2]: The soil characteristics were taken from New Zealand's National Soils database. The values represent the mean and standard deviation for five of the dominant soil types in each area.
[3]: The fractions of different irrigation management, namely 'efficient', 'over-irrigated', and 'over-irrigated with frost protection'were estimated based on expert opinion and relate to the total area under kiwifruit in the various regions.
[4]: Soil water available at field capacity (= FC) in 0-2 m depth. In New Zealand FC is defined as the water stored at a soil matric pressure potential of -60 hPa.
[5]: Plant available soil water (= PAW) in 0-2 m depth. This is defined as the water available in a soil between the soil matric pressure potential of -60 hPa (= FC) and of -15,000 hPa (= permanent wilting point)

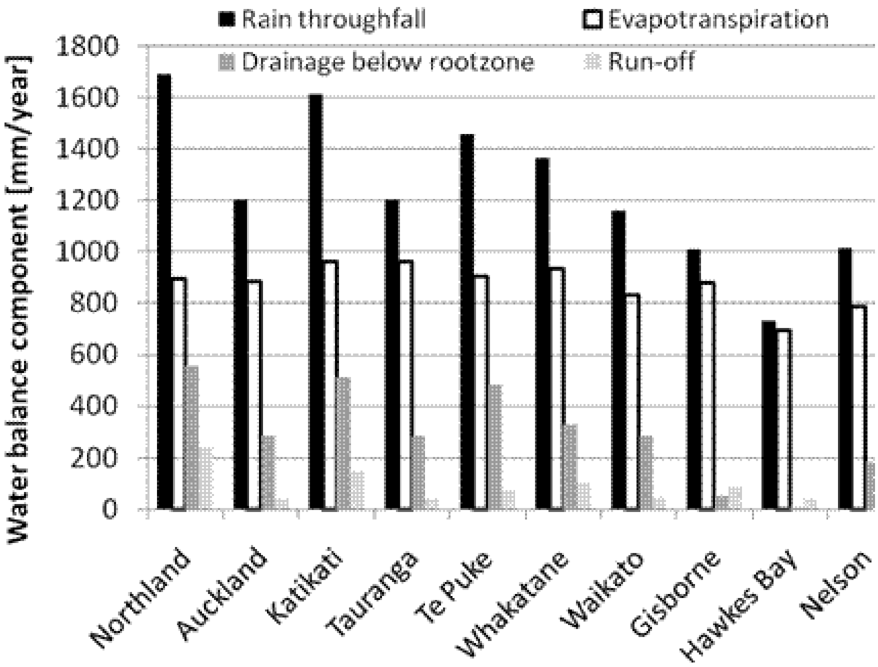

Figure 1: The key components of the water balance for the main kiwifruit growing areas in New Zealand, averaged over the time period of 1973-2010. Meteorological data were sourced from the National Institute for Water and Atmosphere (NIWA) and soil properties were sourced from the National Soils Database. We used the SPASMO model for estimating the water balance components under kiwifruit production. The modelled components are the rain throughfall (RF^*), the drainage below the root zone (D), the evapotranspiration of the soil-plant-atmosphere system (ET_c), as well as the run-off (RO).

We considered two irrigation strategies to assess the impact due to the grower's water management practices. We termed them 'efficient irrigation' and 'over-irrigation'.

In efficient irrigation management, an aliquot of 10 mm of irrigation water is applied every time that the water stored in the 0-2 m depth is less than 50% of the plant-available water (PAW; Tab. 1). This strategy follows the 'little and often' approach. In the case of over-irrigation, some 20 mm of irrigation water is applied every time the water stored in the top 2m of soil is less than just 75% of PAW. Both scenarios, the efficient irrigation and the over-irrigation, are widely used management practices in New Zealand kiwifruit orchards.

Predictions of the soil-water dynamics and fruit production in a kiwifruit orchard system

We used Plant & Food research's mechanistic Soil-Plant-Atmosphere-Model (SPASMO) to predict soil-water dynamics and fruit production from kiwifruit orchards across the major growing areas of New Zealand (Green et al., 2006; Green and Clothier, 1988; Green and Clothier, 1995; Green et al., 1999; Vanclooster et al., 2004). This model considers water, solute (e.g. nitrogen and phosphorus), and pesticide transport through a 1-dimensional soil profile. The soil water balance is calculated by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the soil profile. The model includes components to predict the carbon and nitrogen budget of the soil. These components allow for a calculation of plant growth and nutrient uptake, various exchange and transformation processes that occur in the soil and aerial environment, recycling of nutrients and organic material to the soil biomass, and the addition of surface-applied fertilizer and/or effluent to the land. Model results for the water balance are expressed in terms of mm (= one litre of water per square metre of ground area). The concentration and leaching losses of nutrients are expressed in terms of mg L^{-1} and kg ha^{-1}, respectively. All calculations run on a daily basis and the results are presented at the orchard block scale.

Profile descriptions of the soils hydraulic and physical properties were derived using data from New Zealand's National Soils Database. For each soil horizon, individual water retention curves were fitted using the van Genuchten model. Typical values were chosen for saturated hydraulic conductivity based on soil texture and drainage class.

Plant growth was modelled using a potential production rate per unit ground area that is related, via conversion efficiency, to the amount of solar radiant energy intercepted by the leaves. Daily biomass production was divided into four parts: foliage, shoots, fine roots and fruit. A simple allometric approach was used to allocate new growth, and the associated nitrogen content of each plant component. Model parameters and biomass data for green kiwifruit are described in (Green et al., 2007). Typically, soils around the Te Puke region can store about 900 mm of water (Tab. 1, Fig. 1). Kiwifruit vines are deciduous (i.e. they have no leaves from mid-May to mid-September) and the understory is normally grassed. The roots of kiwifruit extract water from the soil profile for about 9 months of the year, with the highest transpiration losses occurring in the summer (December-March, Fig 2).). Less rainfall occurs over the summer than is transpired from the vines and the understory grasses, and so the water store typically declines through the growing season. Thereafter, there is excess rainfall over winter (June-September) that helps to recharge the soil water store every year. In recent field experiments we have measured the water stored in the top 2 m of the soil of a kiwifruit orchard near Te Puke between 2005-2007 by using Time Domain Reflectometry (TDR) (Fig. 2). This dataset served to validate the performance of SPASMO for modelling the soil water dynamics in the Te Puke area (Fig. 2).

The impact of kiwifruit production on water scarcity and quality strongly depends on the climate, and in particular on the amount and timing of the rainfall. We have simulated the water dynamics and kiwifruit production over the 37-year time period 1973-2010 so as to account for short-term variability in the weather patterns. We then averaged the water balance components and kiwifruit yields to assess the impact of kiwifruit production on water scarcity and quality. This procedure avoids an analysis that is biased towards the weather conditions of any particular year.

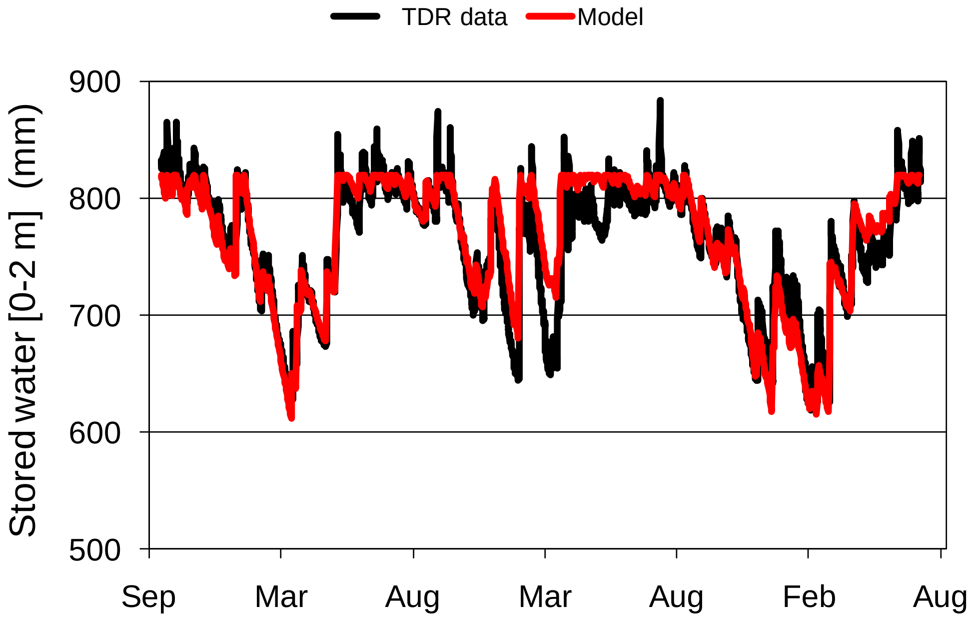

Figure 2: The dynamics of **ΔS,** the amount of water stored in the top 2 m of the soil profile of a mature kiwifruit vine in the Te Puke area of New Zealand (2005-2007) as measured using an array of Time Domain Reflectometry (TDR) probes, along with the prediction using the mechanistic SPASMO model. No irrigation was used on this orchard.

Results and Discussion

Impact of kiwifruit production on the scarcity of freshwater resources in soil and groundwater

Over the 'kiwifruit year' from April to April, the net change of the soil water store is negligible for all growing regions of kiwifruit (Fig. 3).

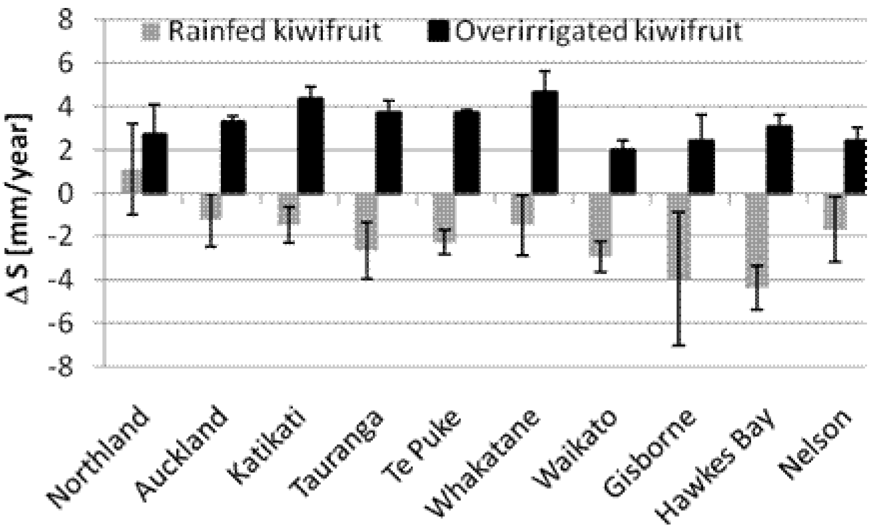

Figure 3: The influence of the growing region and water management on the net change of the freshwater storage in the soil □ S [mm/year] under kiwifruit production. The bars are not error bands, but rather they denote ± one standard deviation of the variation caused by the different soils considered in each of the regions (Tab. 1).

Typically, the soil water store is depleted from spring to autumn (e.g. September to March), and then recharged during winter (Fig. 2). There is not net depletion of the soil water store over the long-term by kiwifruit production. At the same time, that water which is stored in the soil is essential for agricultural production. About 78% of crop water use is derived from rainfall that is stored in soils (De Fraiture and Wichelns, 2010). We conclude that kiwifruit production has no influence on the scarcity of freshwater stored in soils over the timeframe of one year. Another study, which addressed the impact of broccoli production on the scarcity of freshwater, also suggested that the dynamics of the freshwater stored in soils can be neglected (Mila i Canals et al., 2010; Mila i Canals et al., 2009).

Model outputs showed large differences in groundwater recharge for the different growing regions of kiwifruit in NZ due mainly to differences in rain throughfall and evapotranspiration (Figs 1 and 4). For example, in Northland, the region with the highest rain throughfall (Fig. 1), the annual net groundwater recharge under rainfed kiwifruit is about 800 mm/year (Fig. 4). In Hawke's Bay, the region with the lowest rain throughfall, it is only about 40 mm/year (Fig. 4). According to our calculations all rainfed kiwifruit systems maintain groundwater recharge. In contrast, the practice of overirrigation would lead to a net depletion of the groundwater in two of the growing regions; Gisborne and Hawke's Bay. However, these regions are not very important for ZESPRI®'s kiwifruit production. They only contribute 2.2% of the national harvest (Table 1).

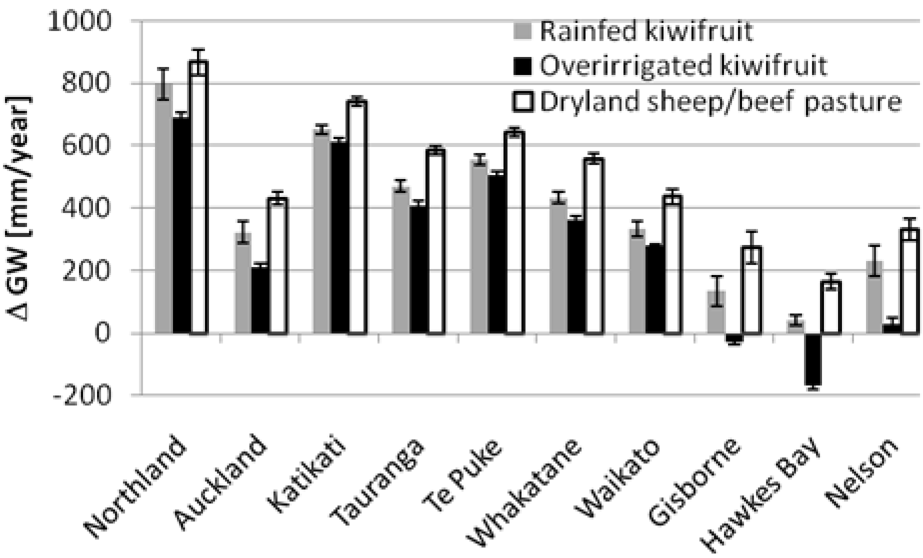

Figure 4: The influence of growing region and water management on the net change of the freshwater storage in the aquifer GW [mm/year] under kiwifruit production, along with extensive sheep/beef pasture. As noted before the bars represent only the variation caused by the different hydraulic characteristics of the soils in the various regions.

It is obvious that a net depletion of an aquifer, as is the case for overirrigated kiwifruit in the Hawke's Bay region (Fig. 4), would increase the scarcity of freshwater resources. However, how much groundwater recharge under kiwifruit production is enough to avoid freshwater scarcity? To answer this, we need to adress three main issues.

Firstly, 'enough groundwater recharge' has only a local meaning. Groundwater recharge, for example, maintains river flows, water levels in wetlands, and meets the water requirements of society and industry. These ecological and societal requirements are specific, and relate to the particular local conditions of each aquifer system. Therefore, we would need to identify a desired groundwater recharge value separately for each aquifer system. Ecological requirements could be based on science, and would be assumed to be fairly stable. However, the societal requirements involve political decisions and might change over time, as for example with rapid population growth and grwoing water demands of cities.

Secondly, the groundwater recharge of a (regional) aquifer system seldomly only depends on a single land use, such as kiwifruit. Rather, the uses and demands of all land-uses and water extraction schemes from an aquifer system need to be considered. The mozaic of land-uses and water extraction schemes in a catchment usually evolves over time as will the aquifer-wide groundwater recharge.

Thirdly, one could ask are there 'better' alternatives compared to kiwifruit production with respect to groundwater recharge, if for example, the groundwater recharge under kiwifruit were deemed to be too small? In theory, bare soil, namely an absence of productive land use, would be the most favourable solution for maximising groundwater recharge since evaporative losses are minimized. However, this would pose a multitude of other problems ranging, from the degradation of the soils by erosion, through to a collapse of the financial returns of the local farming community, and an absence of food to sustain community needs.

Instead of using bare soils as the baseline alternative, we compared groundwater recharge under kiwifruit production with extensive sheep/beef pastures (Fig. 4). In most kiwifruit growing regions, extensive sheep/beef pasture would have been the land-use prior to kiwifruit. This comparison therefore mimics the 'net' green water assessment carried out by SAB-Miller in considering the impact of land-use on the water footprints of beer from either South Africa or the Czech Republic (SABMiller and WWF, 2010). Extensive sheep and beef land-use would likely have the highest groundwater recharge. On average, about 30% less groundwater recharge occurs under rainfed kiwifruit, as compared to extensive sheep/beef pasture. The values range from only 9% less groundwater recharge in Northland up to 75% less in the Hawke's Bay (Fig. 4). In five of the regions (Northland, Katikati, Tauranga, Te Puke, Whakatane) that contribute 84% of the national kiwifruit harvest, the groundwater recharge under rainfed kiwifruit is at least 80% of that under extensive sheep/beef pasture. We attribute this difference to the fact that kiwifruit have much deeper rootsystems (1.5 m on average cf 0.5 m for pasture), and they have higher transpirional losses over summer cf rainfed pasture. More transpiration means less drainge, all other factors being equal.

It seems that in order to better inform markets and consumers about water scarcity, the comparison of the groundwater recharge of the two different land-uses needs to be product based. We consider that a comparison of the groundwater recharge per kg of meat or wool versus per kg of kiwifruit seems to be meaningless, for the products themselves are not comparable in general, and certainly not when considering a unit weight basis.

From this brief discussion of the three groundwater-recharge issues we conclude that it is outside the scope of this study to identify a desired groundwater recharge value. This question needs more research.

Another way of benchmarking the impact of kiwifruit production on groundwater recharge would be to relate the amount of groundwater recharge to the amount of rainfall. Across our regions, this fraction ranges in rainfed kiwifruit orchards from 46% in Northland to 5% in the

Hawke's Bay. In the five key growing regions pf Northland, Katikati, Tauranga, Te Puke, and Whakatane, the fraction is more than 30%, which is close to the 'optimal value' of 37% that was recently recommended for all of New Zealand (Smakhtin et al., 2004). These are the same five regions that have at least about 80% of the groundwater recharge of extensive sheep/beef pasture. We conclude, that kiwifruit produced in New Zealand in general have either a positive, or at least no adverse impact on freshwater scarcity of groundwater. Simultaneously it highlights that future development of new kiwifruit production areas should address the issue of freshwater scarcity in aquifers, and therefore focus on those five regions and should possibly avoid the Hawke's Bay area, climate-change impacts notwithstanding.

Deterioration of quality of freshwater resources

An important threat to freshwater utility, local biodiversity and aquatic habitats is the degradation of water quality by eutrophication. For groundwater resources in New Zealand, this is mainly caused by nitrate from agricultural land use (Anonymous, 2007).

One first needs to establish a relevant background level against which to judge a degree of deterioration. Across the kiwifruit growing areas of New Zealand, elevated NO_3-N concentrations were detected in wells of New Zealand's National Groundwater Monitoring Programme between 1995-2006 in Northland, the Waikato, Hawke's Bay and Nelson (Anonymous, 2007). Of the 956 sites for which the median NO_3-N concentrations in 1995-2006 were derived, 4.9% exceeded the New Zealand Drinking Water Standard of 11.3 mg/l NO_3-N, and 10.3% exceeded the trigger value for ecosystem protection for groundwater of 7.2 mg/l NO3-N. About 30% of all sites have NO_3-N concentrations above 3.5 mg/l NO_3-N which is suggested as a NZ-specific indicator value for showing human influence (Daughney and Reeves, 2005). The overall median NO_3-N concentration was 1.3 mg/l NO_3-N (Anonymous, 2007).

The impact of agricultural land-uses on the quality of freshwater resources can be assessed using either a target concentration (e.g. mg/ l of NO_3-N; Fig. 5) or a target loading rate (e.g. kg NO_3-N/ha; Fig. 6) of the leachate leaving the root zone and destined for groundwater.

The predicted annual average nitrate concentrations leaving the root zone are, across all regions, below the threshold of both the drinking water standard and the trigger value for ecosystem protection. The values, however, vary by about a factor of 5; ranging from 1 mg/l in Northland and the Waikato through to about 5 mg/l in the Hawke's Bay.

The different criteria discussed previously, vary by one order of magnitude, ranging from the median groundwater concentration of 1.3 mg/l to the NZ drinking water standard of 11.3 mg/l. The choice of given threshold value will determine how the impact of NZ kiwifruit production on the quality of freshwater resources is rated. For example, if the median groundwater nitrate concentration is used as the chosen value, then the drainage water from kiwifruit production of 80% of the regions and the national average does indeed exceed it. However, if either the NZ drinking water standards, or the trigger value for ecosystem protection, are selected instead, then none of the regions, or the national average, exceeds it. More discussion is needed as to how such a threshold value should be chosen to indicate the impact and trade-offs of agricultural production on freshwater quality.

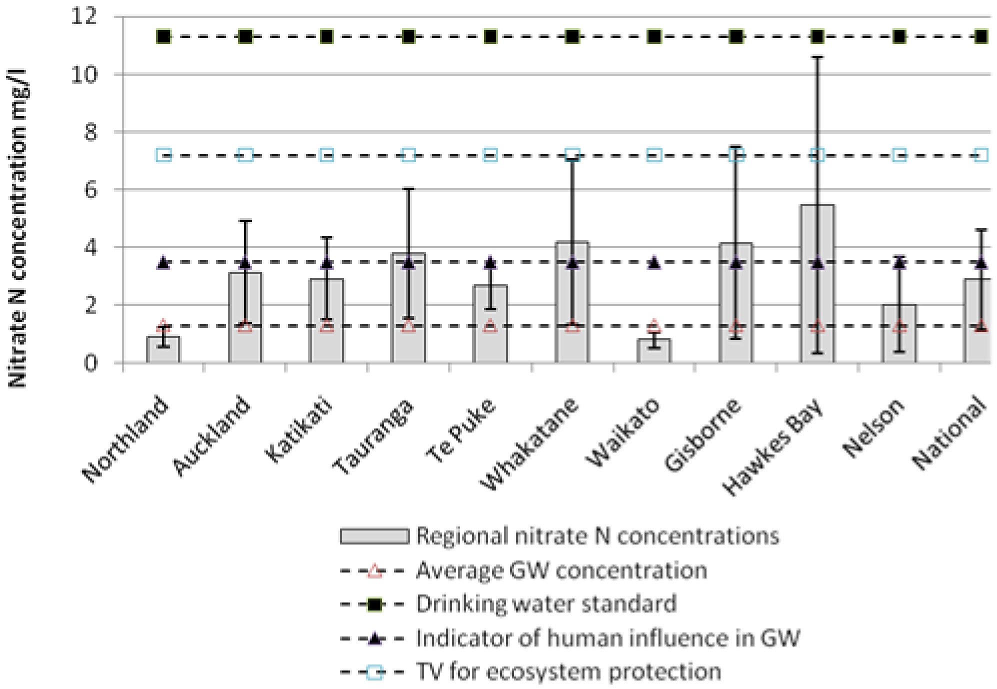

Figure 5: Simulated annual average NO_3-N concentrations in the leachate leaving the root zone of ZESPRI® GREEN kiwifruit orchards for different regions, and for the national average. The dashed lines represent some possible contamination threshold values for assessing the impact on the freshwater ecosystem (see text for details). The bars denote ± one standard deviation, and represent only the variation caused by the different soil properties within each region.

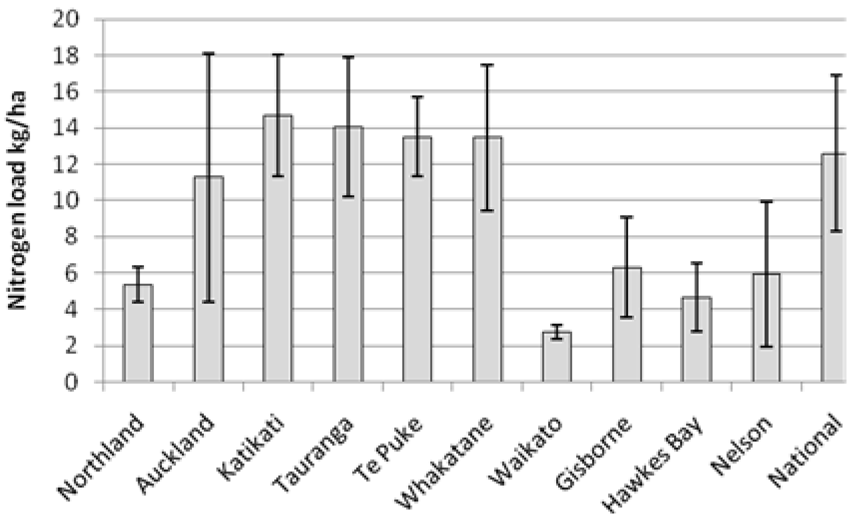

Figure 6: The influence of region on the annual average (April to April) nitrate nitrogen load leaving the rootzone per canopy ha of ZESPRI® GREEN kiwifruit orchards. The bars denote ± one standard deviation, and represent only the variation caused by the different soil properties within each region.

The annual average (April to April) nitrate-nitrogen loads leaving the root zone of kiwifruit production vary by a factor of five ranging from about 3 kg/ha in Waikato to about 15 kg/ha in Katikati. The ranking of nitrogen concentrations and nitrogen loads for the different regions is different. For example, in the relatively dry regions such as the Hawke's Bay and Gisborne (Fig. 1), the concentrations of nitrate in the drainage water might be high (Fig. 5), but when multiplied by the amount of drainage water the resulting nitrogen load is small (Fig. 6).

Currently in New Zealand, there are no guidelines against which to assess what nitrogen loading would indicate an adverse impact of kiwifruit production on the quality of the freshwater resources of a particular aquifer. Furthermore, other land-uses are likely to have quite different eutrophication impacts on groundwater, and how these loadings on the groundwater systems might be partitioned would be a challenging exercise. As with our earlier discussion about the optimal value for groundwater recharge, a recommendation of pollutant would need to consider the specific hydraulic and hydrologic conditions of the aquifer. This would need to consider, as just noted, the nitrogen loads from all sources, as well as the particular physicochemical conditions of the aquifer. More discussion and research is needed as to which nitrogen load should be chosen for indicating there is, or there is not, an impact of kiwifruit production on freshwater quality of the groundwater.

Representation of the impact of kiwifruit production on the freshwater resources in soil and groundwater by water footprints

By definition, the green-water footprint indicates the depletion of those freshwater resources stored in the soil that originate from precipitation, and the blue water footprint is assumed to indicate the status of the freshwater resources stored in the groundwater. Here we use model outputs to compare two different concepts for calculating the footprints. Our concept (Approach 1) quantifies the net change in the resources, whereas the other of the WFN (Approach 2) only accounts for the consumption of 'green' or 'blue' water from each store.

We have evaluated the performance of both approaches in two steps. First, we have already expressed mathematically the relation between the footprints derived by each approach in relation to the net change of the freshwater stored in soil (ΔS) and groundwater (ΔGW). The latter two are ideal terms for hydrologists to quantify possible depletion of either freshwater resources in the soil or groundwater in connection with kiwifruit production. Now, we will use a regression analysis with the regional footprints as the dependent variable, with the net regional changes of the freshwater stored in the soil and groundwater as the independent variables. The higher the regression coefficient, we would consider the better the water footprint metric for explaining the impact of kiwifruit production on freshwater resources.

Green water footprint

Mathematically it can be shown (Equation 5a) that under rainfed conditions the net change of green water, $\Delta\Gamma$ (our Approach 1), is identical to the net change in soil water, ΔS, multiplied by -1. The regional green-water footprint is then calculated as the regional net change of green water, $\Delta\Gamma$, weighted by the regional kiwifruit productivity (Equation 6). The green water footprint following Approach 1 (green WFP^1) can explain 98% of the variability of ΔS across regions (Fig. 7, top). There is no significant correlation between the green-water footprint and ΔS if the orchard is irrigated. However, this is not surprising as the definition 'green' water only considers water in the soil originating from precipitation.

If the WFN's Approach 2 were taken (Equation 5b), then it can be seen that the green water consumption ΓC does not equal ΔS, irrespective of the orchard being irrigated or not. The weak correlation of the green-water footprint derived from Approach 2 with ΔS is confirmed by the low correlation. The green WFP^2 can only explain about 50% of the regional variability in Δ S (Fig. 7, bottom).

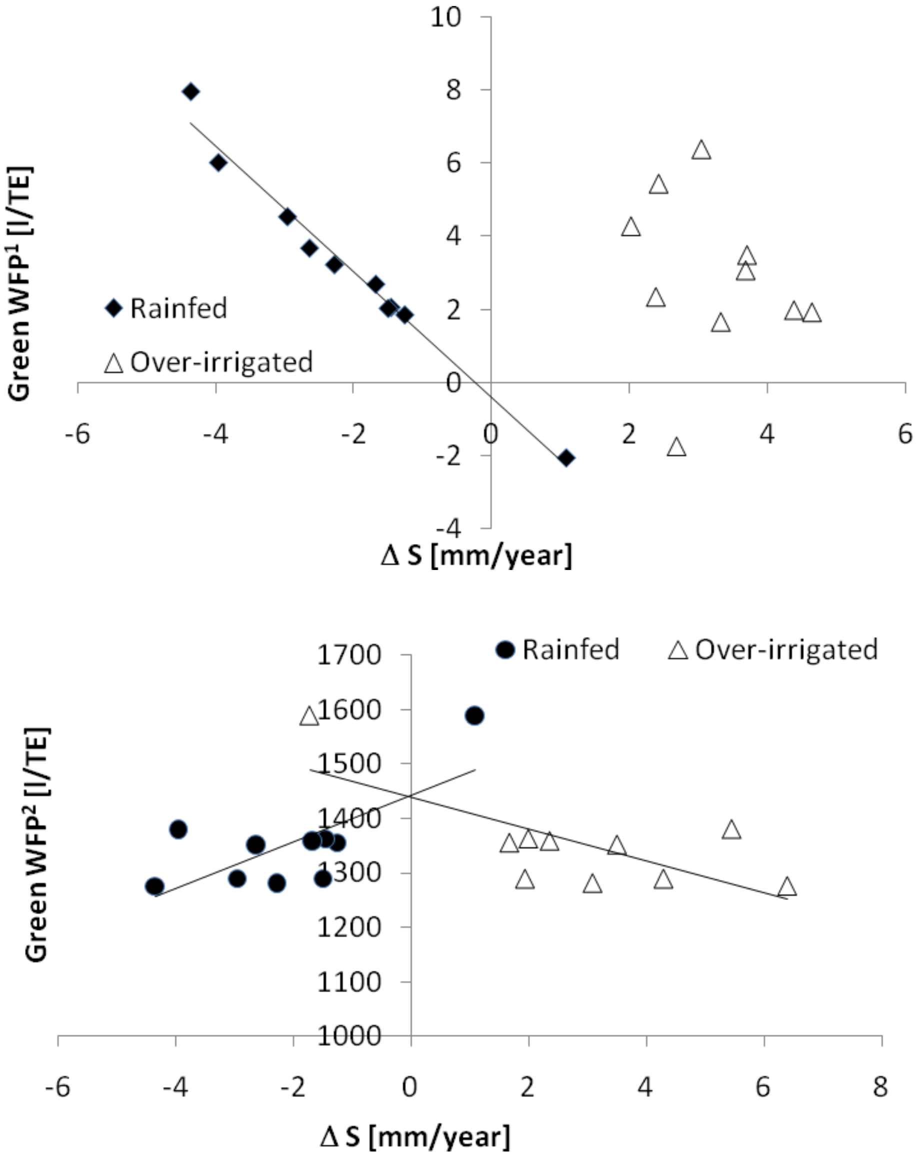

Figure 7: The regional green-water footprints as a function of the net change in the soil water storage over one year, ΔS. The results for a rainfed (solid symbols) and an over-irrigated system (open symbols) are shown separately. **Top**: Approach 1 (Green WFP^1). The regression equation for the rainfed system is Green $WFP^1 = -1.73\ \Delta\ S - 0.42$ with an R^2 of 0.98. The regression for the over-irrigated system is not significant. **Bottom**: Approach 2. The regression equation for the rainfed system is Green $WFP^2 = -42.66\ \Delta S + 1442.9$ with an R^2 of 0.52, and for the over-irrigated system it is Green WFP2 = -29.24 delta S +1438 with an R^2 of 0.52.

The values of the green water footprints calculated with the two methods differ by more than two orders of magnitude. With Approach 1 they are, on average, about 5 L/TE and with Approach 2 about 1350 L/TE. Approach 1 recognizes that there is negligible net change of soil water per unit of product over the course of the kwifruit year, while Approach 2 only reflects the total evapotranspiration of soil water per unit of product.

We conclude that Approach 1 is better suited to represent the net change of soil water, but only for rainfed systems. Also, we argue that only Approach 1 properly considers all relevant terms of the water balance of the soil-water store. For example, while Approach 2 only focuses on the loss of water from the store by evapotranspiration, Approach 1 also recognises the 'natural' replenishment of soil water by rainfall. However, as pointed out earlier, in our opinion there is no real need to evaluate a green-water footprint for kiwifruit, since freshwater depletion in soils is never an issue in our high rainfall climate over a yearly timeframe.

Blue water footprint

The net change in blue water, Δ B (Approach 1), equals the groundwater recharge multiplied by -1. It is, therefore, a rational representation of the change of freshwater stored in the aquifer below the kiwifruit orchard. With this approach, the blue water footprints (Blue WFP^1) can explain 97% the variability of the regional groundwater recharge below kiwifruit orchards, in both rainfed and overirrigated systems (Fig. 8, top).

The blue water consumption, Δ BC (Approach 2) does not equal groundwater recharge (Equation 9). This is also confirmed by its poor representation of the variability of regional groundwater recharge from overirrigated kiwifruit orchards (Blue WFP^2) with an R^2 of only 0.63 (Fig. 8, bottom). The blue water footprints of rainfed kiwifruit orchards is, according to the definition of Approach 2, zero.

The values of the blue-water footprints calculated by the two different methods differ, with the green water footprint comparison, by two orders of magnitude. With Approach 1 they are, on a regional average, about -500 l/TE and with Approach 2 they are about 100 l/TE. The difference in values, and their changed signs, emphasizes the fundamentally different meaning of the blue water footprints when calculated either with Approach 1 or 2. In Approach 1, a tray of kiwifruit from an over-irrigated system still delivers a net groundwater recharge of on average about -500 l/TE, whereas with Approach 2 the production of a tray of kiwifruit costs on average about 100 l/TE. Only Approach 1 contains all the hydrological processes making up the water balance that relates to groundwater. Therefore, it reflects better the influence of the local climate, for example the unimpeded drainage due to rainfall that is typical for some of New Zealand's kiwifruit growing areas.

We defined the change in blue water, ΔB, for Approach 1 to be equal to the groundwater recharge multiplied by minus one. The common perception, for example, from the work around carbon footprints, is that the more positive, or higher, the value of an environmental footprint is, the more adverse is the impact on the environment. In the area of carbon footprints there are also carbon 'credits' which indicate a positive impact for the environment, say by sequestration of carbon in the soil. With respect to freshwater scarcity in aquifers, groundwater recharge is a 'credit'. Instead of 'credits' we have used here the negative value scale. 'Credits' would also be misleading in the area of water footprints. As discussed above, depending on the local hydrology, a negative water footprint of some value is actually needed to sustain the local ecosystem services that are dependent on groundwater.

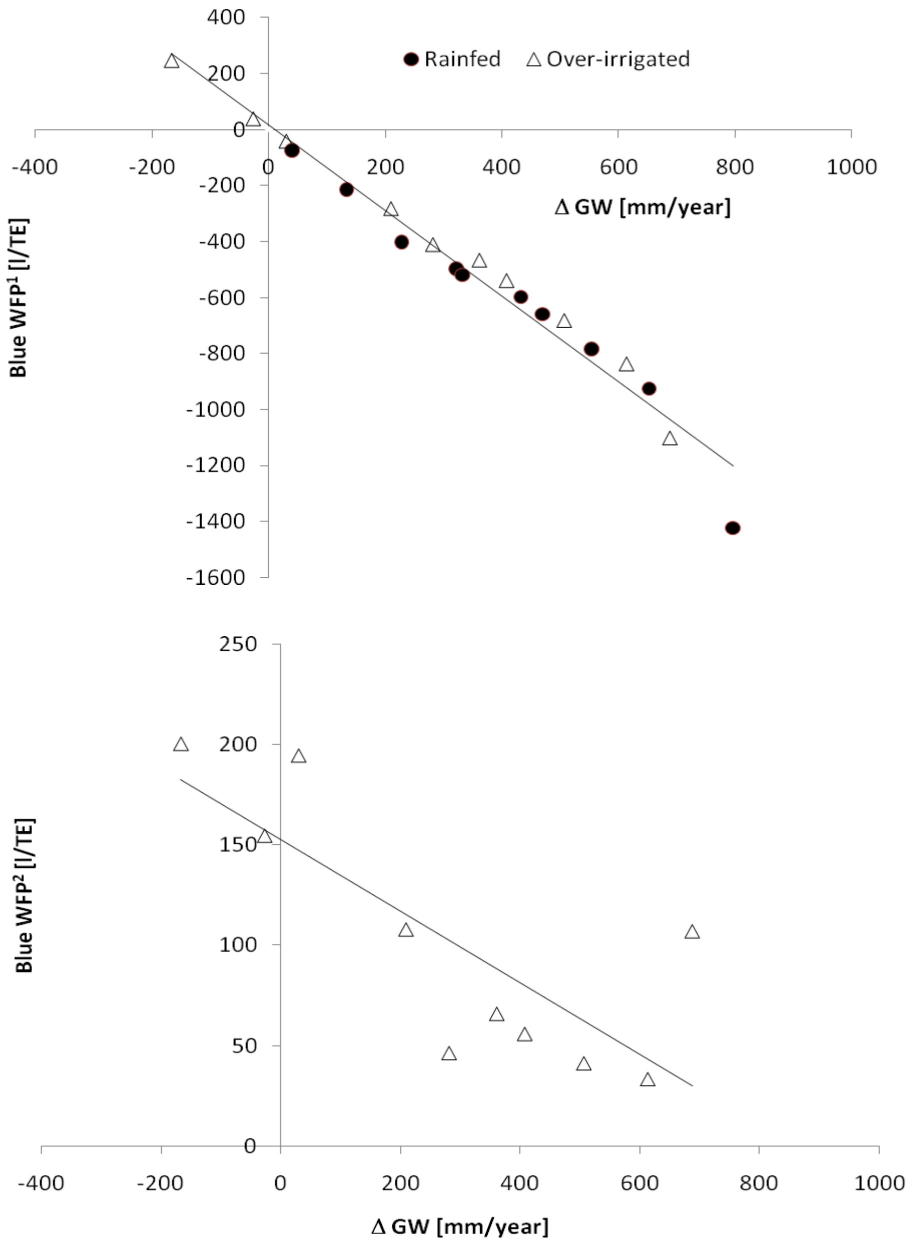

Figure 8: The regional blue-water footprints as a function of the net change in the groundwater storage over one year, ΔGW. The results for a rainfed and an over-irrigated system are shown separately. **Top**: Approach 1 (Blue WFP1). The regression equation for the rainfed and the over-irrigated system is Blue $WFP^1 = -1.53\ \Delta GW+16.53$ with an R^2 of 0.97. **Bottom**: Approach 2. The regression equation for the over-irrigated system is Blue $WFP^2 = -0.18\ \Delta GW + 152.5$ with an R^2 of 0.63. In Approach 2, the rainfed system has by definition a blue water footprint of zero.

We conclude that Approach 1 for calculating blue water footprints is better suited to represent the impact of kiwifruit production on groundwater recharge from kiwifruit orchards. However, the blue WFP^1 alone would be sufficient for indicating an adverse impact of kiwifruit production on freshwater scarcity in aquifers if indeed the value were positive, thereby denoting a net freshwater depletion from the aquifer. The latter occurred for over-irrigated kiwifruit production systems in Hawke's Bay and Gisborne. A negative value of the blue WFP[1] is only a first step for indicating either a positive or negative impact of kiwifruit production on freshwater scarcity. Two more steps are needed in this case. First, an agreed value for the regional groundwater recharge, or depletion, from kiwifruit production needs to be identified, as we have discussed above. Secondly, the regression in Fig. 8 can be used to translate this value into an optimal regional blue water footprint. If the actual regional blue water footprint of kiwifruit is more negative than the agreed value, then we can conclude that kiwifruit production in this region has a positive impact on the freshwater scarcity of this particular regional aquifer. If the actual value is more positive than the agreed value, then an assessment needs to be undertaken what kind of land-use might increase groundwater recharge, and, at the same time, determine whether such an alternative land-use were also socially and economically viable.

Grey water footprint

For the grey water footprint there is only one approach. Mathematically, the grey water dilution, GD, is the basis of the grey water footprint, yet it neither indicates if the leachates out of the root zone are below a concentration threshold, nor if a critical pollutant loading rate is relevant (Equation 12). The grey water footprints for kiwifruit had no significant relationship with the regional average nitrate concentrations (Fig. 9). However, they were well correlated with the regional annual nitrogen loading rates (Figs 10, and 11). For example, the grey-water footprints could explain 99% and 67% of the regional nitrogen loading rates, when a natural background concentration of 0 and 1.3 mg NO_3-N/l were assumed, respectively. Different background concentrations (Fig. 10), and different maximum admissible concentrations (Fig. 11) led to different regression equations as how the nitrogen loads are translated into grey water footprints.

This finding highlights how sensitive the absolute value of the grey water footprint is to the selection of the natural background concentration, and the maximum admissible concentration threshold (Equation 12). We recommend that the choice of the value of the background concentration and the maximum admissible concentration always be given in addition to the grey water footprint value. More discussion is needed as to which value is appropriate for both.

We conclude that it is possible to relate the grey water footprint to a pollutant loading rate, for example the annual nitrate nitrogen load, but not to a critical pollutant concentration. This means, for example, that the grey water footprints are meaningless for environmental agencies that use pollutant concentrations as a trigger value for policy action.

The grey water footprint value as such cannot directly inform if kiwifruit production is having an adverse impact on the water quality of the underlying aquifer. The grey water footprints of all land-uses across the aquifer recharge area would need to be considered, as well as the specific hydrological and biochemical conditions of the aquifer.

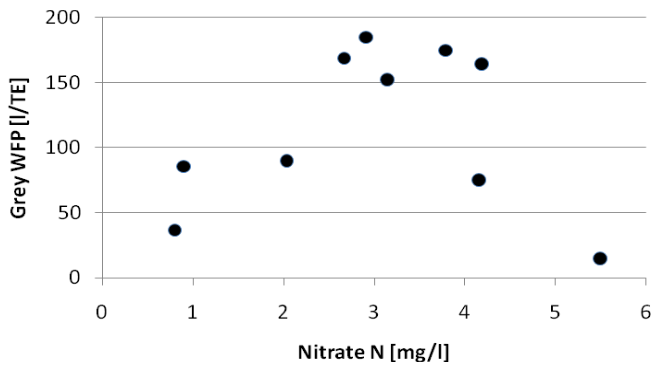

Figure 9: The regional grey water footprints, Grey WFP, as a function of the regional nitrate N concentrations of rainfed kiwifruit orchard systems. For the calculation of the grey WFPs a background 'pristine' concentration of 0.0 mg/l NO_3-N and a maximum admissible concentration of 11.3 mg/l NO_3-N were used.

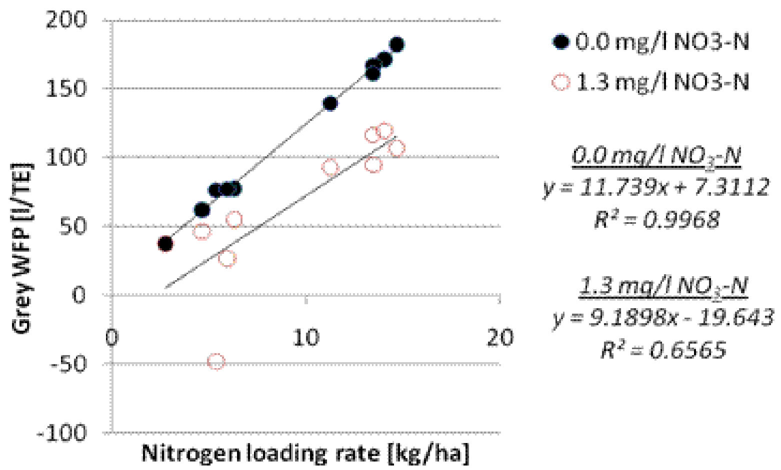

Figure 10: The regional grey WFP as a function of the regional nitrogen loading rate, and for different natural background concentrations. For the calculation of the grey WFPs a maximum admissible concentration of 11.3 mg NO_3-N was used.

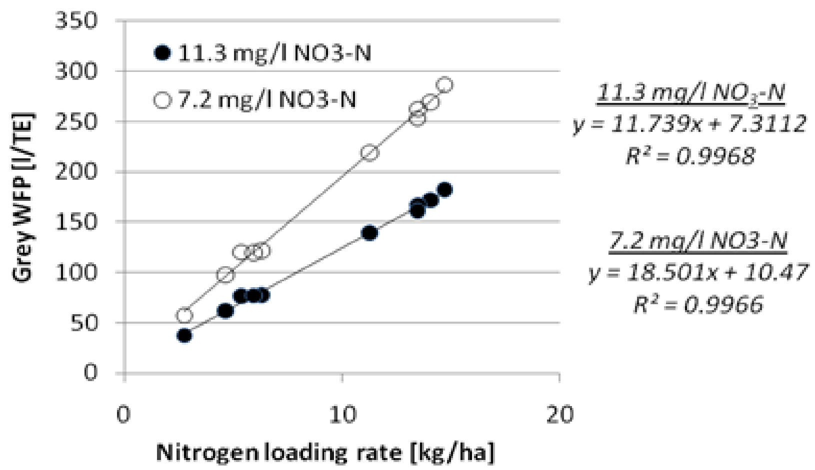

Figure 11: The regional grey WFP as a function of the nitrogen loading rate and for different maximum admissible concentration (11.3 and 7.2 mg/l NO3-N as the drinking water standard, and the trigger value for ecosystem protection). For the calculation of the grey WFPs a natural background 'pristine' concentration of 0.0 mg/l was used.

Conclusions and recommendations

The first objective of this study was to define and quantify a set of hydrological criteria for assessing the impact of NZ kiwifruit on freshwater resources.

Freshwater utilized by kiwifruit is either stored in the soil, or in groundwater. The net change of soil water and the net groundwater recharge were quantified over a yearly timeframe to be hydrological rational indicators of an increase or depletion of freshwater resources by the kiwifruit production system. We found a negligible net annual change in soil water, as the freshwater in the soil is replenished every year by rain. The groundwater recharge showed a large regional variation. A net depletion of groundwater resources occurs only in two regions, namely the Hawke's Bay and Gisborne, and only when the orchards are over-irrigated. Currently, it is not possible to benchmark regional groundwater recharge against a guideline value. More research is needed in this direction. There are five kiwifruit growing regions where more than 30% of the rainfall is transferred to groundwater recharge if no irrigation is used. At the same time these regions contribute 84% of the national harvest. From this it seems that kiwifruit production in New Zealand in general has a positive or at least no adverse impact on freshwater scarcity in groundwater.

Model outputs were then used to assess the impact of regional kiwifruit production on water quality by focusing on nitrate. We used both the nitrate concentration and the nitrogen load leaving the main root zone as indicators of potential contamination. On average, across all regions, the nitrate concentrations in the drainage water were well below the NZ drinking water standard of 11.3 mg/l NO3-N, but above the median concentration of all NZ groundwaters of 1.3 mg/l NO3-N. The nitrogen loads ranged from 3 to 15 kg NO3-N/ha. Currently, it is not possible to benchmark these values against, for example, maximum admissible values indicating a positive or adverse impact of kiwifruit production for the regional aquifers. More research is needed on this.

The second objective of this study was to evaluate and discuss the performance of two different concepts of water footprints for representing the impact of NZ kiwifruit on freshwater resources.

Kiwifruit production has no impact on freshwater scarcity in soils. From this perspective the green water footprint can be discarded. Generally, the green water footprint derived by our net change approach (Approach 1) better represented the impact of rainfed kiwifruit, and by the consumption approach (Approach 2) of irrigated kiwifruit on the scarcity of freshwater stored in soils.

The net change approach (Approach 1) is hydrological rational, unlike the consumption approach (Approach 2), and thereby indicates the impact of kiwifruit on groundwater recharge. Only the net change approach rigorously considers the full hydrology of the production system by including inputs such as rainfall, and outputs such as evapotranspiration. We recommend adopting this definition. The resulting regional product-based blue water footprint is a useful metric that can be directly related to the regional groundwater recharge. Once an agreed value has been defined, the blue water footprint could be benchmarked and serve as an indicator for a positive or negative impact. Already now, the positive blue water footprints of over-irrigated kiwifruit systems in Hawke's Bay and Gisborne indicate a negative impact in the form of groundwater depletion.

The grey-water footprint only informs if pollutant loading rates are acceptable given a threshold concentration. The absolute value is sensitive to the choice of background and maximum admissible concentration value. We recommend that this information must always be given in addition. As with the blue water footprint, benchmarking cannot be done at present as no regionally accepted values exist as to how high loads can be. Nonetheless, with mounting public pressure, this is very likely to change soon.

Overall, we conclude that the blue water footprints derived by the hydrologicall rational Approach one, along with the grey water footprinting metric are a first step towards the quantification of the impact of agricultural production on the scarcity and quality of freshwater resources. These metrics would enable one to compare, on a product by product basis, the impact of production from different regions or countries. Some additional discussion would still be needed to enable one to evaluate the inter-product comparison.

Acknowledgements
The research presented in this paper was funded by The Ministry of Agriculture and Forestry (MAF), ZESPRI International Limited (MAF POL 0910-11522), and internal capability funding from The New Zealand Institute for Plant and Food Research ('Eco-efficient supply chains'). We thank A. Barber, A. Hume, and R. Singh for many fruitful discussions about the subject.

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