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Quantifying and reducing the water footprint of rain-fed potato production part II: a hydrological assessment using modelling supported by measurements

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ABSTRACT

Water footprinting (WF) is mooted to quantify the impacts of production on water resources. The impact of the rain-fed potato (*Solanum tuberosum)* production on water resources was assessed for a kilogram of potatoes at the packhouse gate. The hydrological water-balance method was used and this accounts for all inflows and outflows to quantify the net use of groundwater as the blue WF, and that of the soil-water store as the green WF. The green WF was found to be negligible. The blue WF was negative at −67 L/kg. Thus rain-fed potato production here has no deleterious impacts on the water quantity.

The grey WF, the water required to 'dilute' NO_3–N in the drainage to meet the drinking water standard, was 61 L/kg, of which 56 L/kg was from the cropping stage. The impact of the packhouse phase and the background system was found to be small. However, the average leached NO_3–N concentration of 11.3 mg/L, which is just at the drinking water standard, and the loading of 27.8 kg-N/ha/y during cultivation indicate that a single application of fertilizer at the time of planting has impacts on water quality. Our modelling of different fertilizer application scenarios of two splits, three splits and a late application at 55 days after planting reduced the annual average NO_3–N concentrations to 10.5, 10.3 and 9.5 mg/L respectively. Potato yield was not compromised. The grey WF would be reduced to 50.6, 50.9 and 48.9 L/kg respectively for these fertilizer scenarios.

1. Introduction

Potatoes provide more calories, vitamins and nutrients per area of land sown than other staple crops (Nunn and Qian (2011). In New Zealand, potato is the largest vegetable crop in terms of area under cultivation. There are 10,500 ha of farmland under potato cultivation (Potatoes New Zealand, 2012). Potatoes are grown in all parts of the country, all year round, under different management practices including irrigation or rain-fed. They are grown commercially and in home gardens. Crop development programmes in recent years have led to highly productive potato cultivars that require intensive management and high inputs of fertilizers, other agrichemicals and irrigation. Drainage from such highly productive agricultural lands is increasingly perceived as an important contributor to off-site environmental impacts (Crush et al., 1997; Francis et al., 2003; Skaggs et al., 1994).

Water footprinting (WF) is being considered as a metric that can be used to understand the environmental impacts of water use and water-borne discharges. Among the different methods that have been proposed for water footprinting, the hydrological water-balance method has shown a better understanding of the local hydrological impacts of agricultural production systems (Deurer et al., 2011; Herath et al., 2011, 2013a, 2013b). Because of the difficulty of measuring the green and blue water fluxes and the challenge of quantifying the leaching and runoff of agrichemicals to surface and/or groundwater bodies, the WF calculations have been based on many assumptions. For instance, most grey-water footprint calculations have been based on the crude assumption that a fixed fraction of the applied fertilizer is lost through leaching (Chapagain et al., 2006; Dabrowski et al., 2009). This is a rough approximation that excludes critical factors such as different soil types, various agricultural practices, variable local soil hydrological conditions and interactions among the different chemicals within

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the soil. There is a lack of information on measured soil water content dynamics, drainage and leachate under the field conditions of agricultural production that can be used in WF assessments. However, the water and nutrient dynamics vary from year to year depending on the weather conditions. Hence a significant temporal variability is expected in the measured WFs. Field measurements used to capture this variability are time consuming, expensive and labour intensive. Therefore, combining field measurements with modelling should provide a useful tool to estimate the long-term average WFs of a production system.

The main objective of this study was to assess the impact of the life cycle of a fresh potato production system on water resources in the Manawatu region in New Zealand by using the concept of water footprinting. A mechanistic modelling approach that was robustly supported by field measurements was carried out. We also aimed to assess the effect of nitrogen fertilizer management on both the grey-water footprint and the nitrate loadings from the production system to identify improvement options that would reduce the impact on water quality.

2. Methodology

A life-cycle based approach was used to assess freshwater use and its impacts along the potato production chain. The system boundary was established from raw-material acquisition, through cultivation and crop production to market delivery from the packhouse gate. The functional unit was a kilogram of fresh potatoes ready for dispatch at the packhouse gate. The life cycle of this system primarily consists of two phases: the crop production phase in the field, and the packhouse phase in which the harvested potatoes are cleaned and packed ready for market distribution. These two systems were studied in detail. As seed potatoes are sourced externally, this system was assessed separately.

2.1. The crop production phase

The study was conducted on a commercial-scale potato production system in the Manawatu Region of New Zealand. The soil type was Manawatu fine sandy loam (a Dystric Fluventic Eutrochrept) (Clothier et al., 1978) and the average annual rainfall was 940 mm over a 40-year period (1972–2012). Irrigation was not applied, since there was generally sufficient rainfall to meet the crop's water demand. To date, most water footprinting assessments of agricultural products have been carried out by only considering the planting to harvesting phase of crop production. However, the changes that can occur post-harvest due to organic carbon and nutrient additions from the crop residues to the soil is often neglected. In this study, we extended our assessment for the cropping sequence of a potato crop followed by a non-leguminous green cover-crop. This is the rotation commonly practiced by potato growers. The modelling was carried out using the Soil Plant Atmosphere System Model (SPASMO) (Green and Clothier, 1999; Green et al., 2008).

2.1.1. Quantifying water and nutrient dynamics

A mechanistic modelling approach that was robustly supported by field measurements was used to quantify the water and nutrient dynamics and fluxes of the production system with the aim of capturing the spatial and temporal variability. Field measurements were conducted for soil moisture, drainage and leaching over a full year of the potato-cover crop sequence. The soil moisture content was measured using eight three-wire Time Domain Reflectometer (TDR) probes. Six tension fluxmeters (Deurer et al., 2008; Gee et al., 2009) were used to measure the drainage and leaching under the root zone of the potatoes (see Part 1 (Herath et al., 2014) for further details). The field measurements were combined with SPASMO (Green and Clothier, 1999, 1995) to simulate the soil-water dynamics and solute transport by considering a 40-year period (1972–2012) of actual weather data for the site (NIWA, 2012).

The SPASMO schema (Green and Clothier, 1999, 1995; Green et al., 1999) is a mechanistic model that considers water, nutrient, and pesticide transport through a one-dimensional soil profile to the base of the root zone. The SPASMO model includes process components that predict the carbon and nitrogen budgets of the soil to enable calculation of plant water use, growth, and nutrient uptake, plus other exchange and transformation processes that occur in the soil and the aerial environment, along with inputs from land management practices (Green et al., 2008). This model has been validated across a wide range of New Zealand soils under various plant and crop types for a diverse range of climatic conditions and management practices (Green and Clothier, 1999, 1995; Green et al., 1999; Green et al., 2008). The SPASMO model enables prediction of the yield by capturing sunlight and through biomass partitioning in different plant parts as a function of temperature, nutrients and soil water. Here, this model's prediction was verified against our measurements of tuber dry matter content taken over every two week intervals.

Here, we considered a typical practice of potato planting in early October, harvesting in late March and the planting of a non-leguminous green cover-crop that would be ploughed in at the end of the season. The model was validated by comparing the model predictions of daily water and nitrate fluxes with the field measurements of drainage and nitrate leaching at the field sites. Subsequently, the long-term water and nitrate predictions by SPASMO were used to assess the average blue, green and grey-WFs, and to explore various management options by splitting the fertiliser applications to reduce the grey-WF.

2.1.2. Quantifying blue and green water footprints

The blue and green-water footprints were assessed as impacts on water resources by using a full water-balance that accounts for all hydrological inflows and outflows (Deurer et al., 2011; Herath et al., 2011, 2013b). Groundwater was considered the blue-water resource and soil moisture storage was taken as the green-water resource. The net water-balance was quantified by subtracting inflows from the outflows of these blue and green-water resources to account for the net usage. This was then expressed as the blue and green-water footprints (Deurer et al., 2011; Herath et al., submitted for publication, 2013b).

The blue water footprint.

The model predicted hydrological components were used to calculate the blue-WF (Eq. (1) and Fig. 1).

$$WF_{Blue} = \frac{10\{I - (D + R)\}}{Y} \tag{1}$$

here, WF_{Blue} [L/kg of potatoes] is the blue-water footprint of the net use of blue water from groundwater, and I is the amount of irrigation water used [mm/y]. Since no irrigation was used in this system, the uptake from groundwater is zero. Here, D is the drainage from the root zone [mm/y], and R is the surface runoff [mm/y]. Since this permeable landscape is flat to undulating, we have assumed that any surface runoff eventually recharges the groundwater resource. Here, Y is the marketable potato yield [tonne/ha/y]. The factor 10 is for the conversion of units.

The green water footprint.

The green-WF was quantified as the net use of soil-water storage, and we modelled this as the difference between outflows and