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The grey water footprint of milk due to nitrate leaching from dairy farms in Canterbury, New Zealand

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ABSTRACT

The Canterbury Region of New Zealand has undergone rapid and significant land use intensification over the last three decades resulting in a substantial increase of nitrate-nitrogen leached to the environment. In this article, we determined the nitrate grey water footprint of milk, which is the amount of water needed to dilute nitrogen leached past the root zone to meet different receiving water nitrate standards per milk production unit. Our analysis revealed the nitrate grey water footprint for Canterbury ranged from 433 to 11,110 litres of water per litre of milk, depending on the water standards applied. This footprint is higher than many estimates for global milk production, and reveals that footprints are very dependent on inputs included in the analyses and on the water quality standards applied to the receiving water. The extensive dairy farming in Canterbury is leading to significant pollution of the region’s groundwater, much of which is used for drinking water. Dairy farming at this intensity is unsustainable and if not reduced could pose a significant risk to human health and the market perception of the sustainability of the New Zealand dairy industry and its products.

KEYWORDS

SDG6: freshwater; grey water footprint; dairy production; New Zealand

Introduction

Water scarcity and water pollution are critical issues in many parts of the world; by 2025, 64 per cent of the world’s population is expected to live in water-stressed basins (Steinfeld et al. 2006). An increasing human population, changing dietary habits and ongoing productivist ideologies have all increased demands and impacts on water. Current demands for water already threaten biodiversity, human health, and recreational uses (Dudgeon et al. 2006; Vörösmarty et al. 2010; Schullehner et al. 2018), and the impacts from climate change is likely to intensify these pressures (Sultana et al. 2014; Gosling and Arnell 2016; Vörösmarty et al. 2010). Crucially, global water scarcity will be driven not
only by shortages of water but also by rendering water unusable through pollution (Hu et al. 2018; Dalin et al. 2017).

One global impact on freshwaters is the exponential increase in nitrogen fertiliser use and related emissions of reactive nitrogen to the environment in stressed catchments (Julian et al. 2017; Erisman et al. 2013). Increasing reactive nitrogen has driven a cascade of negative effects on natural resources and environmental quality, including soil acidification, eutrophication of aquatic systems, coastal dead zones, biodiversity loss, stratospheric ozone depletion, and an enhanced greenhouse effect (Jones et al. 2014; Mateo-Sagasta et al. 2017; World Health Organization 2011). In aquatic systems, nitrate enrichment can stimulate algal and microbial growth, which can have cascading effects throughout the rest of the food web, altering its functioning and stability, by relieving energy, nutrient, and macromolecule growth constraints of consumers (Canning and Death 2021; Wurtsbaugh, Paerl, and Dodds 2019; Dodds and Smith 2016). In some cases, excessive nutrient enrichment can drive excessive metabolic activity that can result in hypoxic conditions that can cause mass asphyxiation, such as fish kills, or metabolic toxicity (Ferreira et al. 2015; Camargo and Alonso 2006; Dodds and Smith 2016).

In addition to the ecological impacts, evidence is now emerging that there are direct human health effects of reactive nitrogen, in the form of nitrate, in drinking water (Schullehner et al. 2018; Temkin et al. 2019). Three recent studies have identified dose–response relationships between exposure to nitrate in drinking water and the increased risk of colorectal cancer (Schullehner et al. 2018; Espejo-Herrera et al. 2016; Temkin et al. 2019). Nitrate-nitrogen concentrations associated with increased risk of colorectal cancer range from 0.87 mg NO₃-N/L (Schullehner et al. 2018) to 1.60 mg NO₃-N/L (Espejo-Herrera et al. 2016). These concentrations are approximately 10-fold lower than the existing Maximum Acceptable Value (MAV) of 11.3 mg NO₃-N/L, set by the World Health Organization in 1958 to protect against methemoglobinemia in infants (World Health Organization 2017).

Reactive nitrogen management presents a global sustainability dilemma as it is essential to food production (Erisman et al. 2013). Until the twentieth century, reactive nitrogen was predominantly obtained through nitrogen fixing bacteria colonising legumes, but increasing food demand drove increased demand for synthetic nitrogen fertiliser from fossil fuels (Erisman et al. 2008). Synthetic nitrogen production has now eclipsed all that produced by natural systems (Erisman et al. 2008), and this disruption of the nitrogen cycle seriously threatens global human sustainability, not only through its impacts on climate, but also through localised impacts on freshwater quality (Liu et al. 2015; Steffen et al. 2015).

Assessing the pressures placed on freshwaters by food production is vital in any attempt to reduce environmental harm, and a well-established method to do this is to calculate the production-related water footprint. A water footprint (WF) determines the volume of freshwater used to produce a given mass or volume of product or a service across the supply chain directly and indirectly, allowing the relative comparison of freshwater impact between products (Hoekstra et al. 2011). The consumptive WF refers to the consumption of rainwater (green WF) and groundwater or surface water (blue WF). The degradative WF is the grey WF, and is the volume of water needed to dilute pollutants produced as a result of a product’s manufacture to the extent that the quality of the receiving water remains above specific water quality standards (Franke, Hoekstra, and Boyacioglu 2013).
A WF allows producers and consumers to compare the water-related impacts of products and has been central to discussions on water scarcity, food security, environmental sustainability, and sustainable development goals (Berger et al. 2021). Pollutants – particularly nitrogen – emitted to water bodies from intensive food production require large volumes of water to be diluted sufficiently to protect human and ecosystem health. Globally, three quarters of the grey WF of nitrogen emerges from diffuse sources, mostly agriculture (Mekonnen and Hoekstra 2015). However, the majority of water footprint studies investigating food systems highlight the blue (irrigation) and green (rain) water footprints (Hoekstra and Chapagain 2008; Hoekstra and Mekonnen 2012; Mekonnen and Hoekstra 2012), and mostly neglecting the grey water component as it does not address water consumption, but rather the amount of water needed to assimilate pollution (Dalin et al. 2017; Eshel et al. 2014).

In New Zealand, increasing emissions of reactive nitrogen to water are a major environmental issue driven by agricultural and horticultural intensification over the last few decades (OECD 2017; Foote, Joy, and Death 2015; Parfitt et al. 2012). Now eighty-five per cent of waterways in pasture catchments (which make up half of the country’s waterways, measured by length) exceed the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG) nitrate-nitrogen guideline trigger value of 0.44 mg NO₃-N/L (ANZG 2018; Ministry for the Environment and Statistics New Zealand 2019). Approximately 37 per cent of waterways in pasture catchments nationally and 54 per cent in the Canterbury Region have nitrate-nitrogen concentrations above 0.6 mg NO₃-N/L the threshold estimated to support achieving the nation’s minimum acceptable level of macroinvertebrate community health standards (Canning, Joy, and Death 2021). A recent comprehensive analysis of the national water quality database concluded that ‘the greatest negative impact on river water quality in New Zealand in recent decades has been high-producing pastures that require large amounts of fertiliser to support high densities of livestock’ (Julian et al. 2017). Furthermore, it is estimated that between 300,000 and 800,000 individuals across New Zealand may be exposed to drinking water with nitrate concentrations associated with increased risk of colorectal cancer (Richards et al. 2021).

The multiple effects of agricultural intensification are starkly revealed by the poor and declining state of water quality in lowland rivers (Julian et al. 2017; Larned et al. 2004; Larned et al. 2016), lakes (Verburg et al. 2010), groundwater, wetlands (Ministry for the Environment and Statistics New Zealand 2019), and estuaries (Plew et al. 2020) as well as their aquatic biodiversity (Canning, Joy, and Death 2021). Furthermore, impacts of freshwater contamination are likely to be exacerbated by reduction of water volumes resulting from increasing water abstraction and irrigation related nutrient loss to the environment. New Zealand has rapidly increased demand for water and now is the highest per capita abstracter of water for agriculture among Organisation for Economic Co-operation and Development (OECD) countries. This has led to the overallocation of many ground and surface water resources (New Zealand Business Council for Sustainable Development 2008; OECD 2017).

Agricultural intensification in the case-study region, Canterbury, began around 1990, with a rapid switch from low intensity sheep and cropping to intensive dairy production. Since then there has been an 11-fold increase in the number of dairy cows from 113,000 in 1990–1.3 million in 2017 (Ministry for the Environment and Statistics New Zealand
This growth required greater fertiliser and irrigation into the typically dry and semi-arid landscape. This resulted in a 117 per cent increase of nitrate-nitrogen leached to the environment, from 15,000 tonnes in 1990–33,000 tonnes in 2017 (Ministry for the Environment and Statistics New Zealand 2019). The impacts of this intensification are also revealed by a 257 per cent increase in nitrate loads in waterways from natural levels (5.4 Gg yr\(^{-1}\) to 19.2 Gg yr\(^{-1}\)) (Snelder, Larned, and McDowell 2017).

In this article, we estimate the grey water footprint of nitrate leaching from producing milk from dairy farms in Canterbury, New Zealand. We focus only on the farm production phase of the dairy supply chain as this production stage is generally the largest WF fraction of farm animal products (Mekonnen and Hoekstra 2012) and as New Zealand dairy systems are pasture based, we focus on the pasture component. We have only considered the nitrate grey WF as nitrogen-related pollution is a major threat to drinking water and freshwater ecosystems in the case-study region (Green 2014). Previous water footprint studies of dairy production were based on the WHO drinking water standards (Deurer et al. 2011; Zonderland-Thomassen and Ledgard 2012), which are greater than recent estimates of concentrations associated with human and ecosystem health impacts. The blue and green water footprints of dairy in Canterbury were not included in this study as they do not vary with different water quality standards and have been previously calculated for Canterbury by Zonderland-Thomassen and Ledgard (2012). As a result, this article estimates the grey WF by benchmarking nitrate pollution against a range of more recent human and ecosystem health nitrate standards.

**Methods and data**

**Study area**

The Canterbury Region (4,534,600 ha) is located at the eastern centre of New Zealand’s South Island (Figure 1). The western half of the region is mountainous and sparsely populated, while the eastern part is flatter, with approximately 750,000 ha of alluvial area known as the Canterbury Plains where most of the intensive agriculture occurs (Webb, Claydon, and Harris 2000; Green 2014) (Figure 1). Much of the region is characterised as dry and lies in stony and porous drainage basins in the rain shadow of the Southern Alps. There is a strong rainfall gradient from west to east across the plains (e.g. >1000 mm/annum on the western foothills on the eastern side of the Southern Alps and around 600 mm/annum on the eastern seaboard (Macara 2016)). Ministry for the Environment (MfE) figures show the land area used for dairy production in 2017 was 359,081 ha (MfE 2019). In the Canterbury region, groundwater aquifers are expansive, spanning much of the plains, with the shallow aquifers being hydrologically well-connected to surface waters, providing a steady baseflow year-round and contributing substantially to surface water chemistry (White et al. 2012). In Canterbury, there are ten groundwater management zones, with most of dairy land in the Waimakariri, Selwyn-Waihora and Ashburton zones. Across the ten zones, a recent survey of 322 wells, ranging from 3 m to 251 m in depth, observed nitrate-nitrogen concentrations ranging between <0.002 and 22 (median 2.7) mg NO\(_3\)-N/L, with the majority of high concentrations occurring in the Ashburton zone (Tregurtha 2021).
Data sources

The load of reactive nitrogen released to the freshwater environment from milk production in Canterbury was calculated using the approach outlined by Zonderland-Thomassen and Ledgard (2012) and used the national model for farm-scale nutrient budgeting and loss estimation in the modelling software OVERSEER® (Wheeler, Ledgard, and Monaghan 2007). OVERSEER® is a mass-balance model that estimates the fate of nutrients in a productive farming system, either as plant uptake, nitrogen leaching and runoff, or as atmospheric emissions. The model input data includes fertiliser application rates and frequency, supplements, effluent application, estimated plant growth, stocking density, irrigation, climate, soil characteristics, and on-farm management practices (PCE 2018). As the model uses long-term average climate data, the nutrient leaching estimates do not represent a single year, rather they estimate the long-term average of a given farming system. OVERSEER® is jointly owned by the New Zealand Ministry for Primary Industries (MPI), the Fertiliser Association of New Zealand and
AgResearch Limited and is recognised as the most suitable tool available for estimating nitrate leaching losses across the diversity and complexity of farming systems in New Zealand (OECD 2017). Both nitrate loss datasets employed in this study were based on the outputs from OVERSEER® version 6. Studies assessing the ability of OVERSEER® to explain observed nitrate leaching and inform calibration have primarily focused on well-drained soils, at a depth of 0.6–0.7 m, in the Waikato and Canterbury regions (representative of this case study) (Science Advisory Panel 2021).

The grey WF for milk production in Canterbury was calculated at two scales: regional and farm scale. For the former we used data for total milk production and nitrate leached past the rootzone (i.e. beyond the potential for plant uptake) for the 2017–18 season over the entire Canterbury Region. Dairy production figures for Canterbury were obtained from the Dairy Statistics annual report released by the Livestock Improvement Corporation® (LIC) in conjunction with the dairy industry organisation representing all New Zealand dairy farmers DairyNZ® (LIC and DairyNZ 2018). We obtained the estimated total nitrate leached from dairy cattle for the 2017–18 season for the Canterbury Region from the New Zealand MfE (Table 1). This corresponded to a mean nitrate nitrogen leaching rate of 67.9 kg/ha/annum for dairy farms in Canterbury.

For the farm scale analysis, we used production data for the 2017–18 season from five individual Canterbury dairy farms. The farms ranged in size from 309 to 500 effective hectares with a stocking rate from 2.1–3.9 cows per ha, characteristics typical for the region (Table 2). Data for the NO₃-N loss for the 2017–18 season was calculated using OVERSEER®.

**The grey water footprint**

We calculated the grey WF for on-farm milk production as:

\[
\text{Grey WF} = 1,000,000 \times \frac{L}{(C_m - C_n)} \times \frac{1}{Y}
\]

where the grey WF is the volume of freshwater in litres per functional milk unit required to dilute the nitrogen leachate to an accepted water quality standard; \(L\) is the estimated net-load of nitrate-nitrogen from the system leaving the root zone from OVERSEER® in [kg/ha/yr]; \(C_m\) is the maximum acceptable concentration [mg/L] for nitrate-nitrogen given by the water quality standard (legal and risk-assessment standards, Table 3); and \(Y\) is the quantity of milk produced in the functional milk units per hectare per year (kgMS/ha/yr, L/ha/yr, kg/ha/yr, or kg FPCM/ha/yr, respectively). \(C_n\) is the natural concentration [mg/L] of nitrate-nitrogen in the receiving water body with no disturbance in the catchment by humans. Following Deurer et al. (2011) and Franke, Hoekstra, and Boyacioglu (2013), the background natural level of nitrate in New Zealand

| Table 1. Milk production and nitrate leaching data for the Canterbury Region. |
|-----------------------------|------------------|
| Parameter                   | Value            |
| Total mass milk solids      | 383,863,830 kg   |
| Total volume of milk        | 4,990,229,790 L  |
| Total mass of NO₃-N leached | 24,393,331 kg    |

1LIC and DairyNZ (2018).
2Volume in litres (L) is milk solids (kg) * 13 explanation below.
receiving water bodies was assumed to be zero (undetectable). The maximum acceptable concentration of reactive nitrogen \( (Cm) \) for different purposes can be found from water quality standards in the literature; the standard is dependent on the end use of the water. For the scope of this article, we used six different NO\(_3\)-N concentration standards for ground and surface water. Groundwater and surface water are often hydrologically well connected in the Canterbury Region (White et al. 2012) and there are multiple end uses of the water. Those relevant to drinking water and protecting the environment and ecosystem services are the most critical (Table 3).

**Water footprint functional production units**

One kilogram of milk solids was used as the primary functional unit of milk production, as most of the milk produced in New Zealand is exported as milk powder, and farmers are paid based on the milk solids component of their production. In order to compare our results with other studies, three other functional units of milk production were also used: namely one litre of milk, one kilogram of milk, and one kilogram of fat and protein corrected milk (FPCM). Production data expressed as kilograms of milk solids were converted to litres and kilograms of milk and kilograms of

**Table 2.** Details of mid-Canterbury dairy farms used for analysis of grey WF.

<table>
<thead>
<tr>
<th>Farm</th>
<th>NO(_3)-N leached past root zone (kg/ha/yr)</th>
<th>Effective area (ha)</th>
<th>Annual irrigation (mm)</th>
<th>Stocking rate (lactating cows/ha)</th>
<th>Total milk solids produced (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>424</td>
<td>474</td>
<td>2.1</td>
<td>382,440</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>363</td>
<td>398</td>
<td>2.9</td>
<td>423,770</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>382</td>
<td>439</td>
<td>2.5</td>
<td>384,615</td>
</tr>
<tr>
<td>4</td>
<td>77</td>
<td>309</td>
<td>398</td>
<td>3.1</td>
<td>378,854</td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>500</td>
<td>474</td>
<td>2.0</td>
<td>406,121</td>
</tr>
</tbody>
</table>

**Table 3.** Water quality limits/standards used to calculate the dairy farming grey WF for the Canterbury Region.

<table>
<thead>
<tr>
<th>Water quality limit (mg NO(_3)-N/L)</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>The trigger value for physical and chemical stressors in lowland, slightly disturbed ecosystems published in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Trigger values are used to assess risk of adverse effects due to nutrients, biodegradable organic matter, and pH in various ecosystem types (ANZG 2018)</td>
</tr>
<tr>
<td>0.87</td>
<td>The threshold value resulting from observed statistically significant increased risk of colorectal cancer for adults exposed to long term average drinking water nitrate concentrations above this concentration (Schullehner et al. 2018)</td>
</tr>
<tr>
<td>1.0</td>
<td>This represents the ‘A’ band limit from the National Policy Statement 2020 (Ministry for the Environment 2020). It was the ‘bottom-line’ proposed by the Ministry for the Environment Science Technical Advisory Group (Joy and Canning 2020). This is also the European Union limit for eutrophication in surface waters (Erisman et al. 2013), and the level III limit for surface water in China (Hu et al. 2018)</td>
</tr>
<tr>
<td>2.1</td>
<td>The value above which a 15 per cent increased risk of colorectal cancer for adults exposed to long term average drinking water nitrate concentrations was reported (Schullehner et al. 2018)</td>
</tr>
<tr>
<td>2.4</td>
<td>The ‘bottom line’ limit value for nitrate toxicity in aquatic life stated by the National Policy Statement 2020 (Ministry for the Environment 2020)</td>
</tr>
<tr>
<td>11.3</td>
<td>New Zealand Ministry of Health’s and World Health Organisation’s drinking water standard maximum allowable value (MAV) (established to protect against methaemoglobinaemia in bottle-fed infants) (Ministry of Health 2017)</td>
</tr>
</tbody>
</table>
FPCM by multiplying the relevant figure by 13 from the online converter Xcheque Pty Ltd 2020 (See https://archive.xcheque.com/tools/milk-quantity-converter). This means that the volume and mass of milk and mass of FPCM milk production functional units are all essentially equivalent.

**Grey water footprint calculation**

The grey water dilution volume required in litres for each kilogram of nitrate-nitrogen lost to receiving water to meet given water quality limits/standards was calculated by dividing 1,000,000 by the limit/standard nitrate concentration in mg NO₃-N/L to get kg to mg (Table 4).

The grey WF was calculated using Equation (1) above. Alternatively, the grey WF was calculated by multiplying the load of pollutant (in kg of NO₃-N) by the greywater dilution volume (in litres/kg NO₃-N; Table 4) to give the total volume of water in litres required to dilute the product. This was divided by the amount of product for the same time period to give a grey WF in litres for each product functional unit.

A worked example with the Canterbury regional data for 2017–18 and using the New Zealand drinking water standard (NZDWS; Ministry of Health 2018) maximum acceptable value (MAV) of 11.3 mg NO₃-N/L (Table 3) is as follows. Using Equation (1), L was first calculated by dividing the mass of NO₃-N leached from dairy cattle in Canterbury in 2017–18 (24,393,331 kg) by the land area used for dairy farming (359,081 ha), namely 67.9327 kg/ha/yr. This result was then multiplied by 1,000,000 and divided by Cm (11.3 mg NO₃-N/L) and then divided by the total volume of milk produced in 2017–2018 expressed as L/ha/yr (namely 4,990,229,790 L divided by 359,081 ha or 13,897 L/ha/yr) to yield a grey WF of 433 L/L milk for the 2017–18 season. Alternatively, the total load of nitrate-nitrogen pollutant from dairy production in Canterbury for the 2017–18 season (Table 1) of 24,393,331 kg was multiplied by the dilution volume of 88,496 per litre (Table 4) giving a total volume of 2,158,712,220,176 L/yr required to dilute that nitrate. Finally, this total volume was divided by the milk production for Canterbury (4,990,229,790 L/yr) to give a grey WF of 433 L/L of milk for the 2017–18 season.

**Sensitivity analysis**

Grey water footprints were also calculated assuming the nitrate-nitrogen leachate load estimated for dairy production in Canterbury for the 2017–18 season was under or over-estimated by 30 per cent (Etheridge et al. 2018).

**Table 4. Dilution volumes required for each kilogram of nitrate-nitrogen lost to receiving water to meet various water quality limits/standards.**

<table>
<thead>
<tr>
<th>Water quality limit/standard (Table 3)</th>
<th>Nitrate concentration (mg NO₃-N/L)</th>
<th>Grey water dilution volume (litres/kg NO₃-N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANZG ecosystem health lowland guideline</td>
<td>0.44</td>
<td>2,272,727</td>
</tr>
<tr>
<td>Colorectal cancer significant increase risk</td>
<td>0.87</td>
<td>1,149,425</td>
</tr>
<tr>
<td>National Objectives Framework (Toxicity) Band A</td>
<td>1.0</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Colorectal cancer 15 per cent increase risk drinking water</td>
<td>2.1</td>
<td>476,190</td>
</tr>
<tr>
<td>NPS 2020 (Toxicity) National Bottom Line</td>
<td>2.4</td>
<td>416,667</td>
</tr>
<tr>
<td>New Zealand drinking water MAV</td>
<td>11.3</td>
<td>88,496</td>
</tr>
</tbody>
</table>
Impact of nitrate grey water footprints for dairy farming in Canterbury

Volumes of water to meet Canterbury dairy nitrate grey water footprints

The volume of groundwater in the dairy impacted Canterbury system available to dilute dairy nitrate inputs was estimated as follows. The mean groundwater recharge from rainfall and irrigation recharge was assumed to be approximately 245 mm/annum. This recharge rate was assumed to be the same as that determined by Etheridge and Hansen (2019) for the Waimakariri and Selwyn zones, where the recharge rate was estimated at 21.0 m³/s for the 270,000 ha land area in those zones. The recharge rate equates to 0.882 billion m³/annum or 28.0 m³/s for the 360,000 ha used for dairy farming in Canterbury. This was multiplied by 1.3 to account for losses to groundwater from irrigation races, rivers and hill fed streams, yielding an estimated total volume of groundwater of about 1.15 billion m³/annum or 36.4 m³/s.

The quantities of water required to meet various water quality limits or standards were estimated by multiplying the respective grey WFs by the mass of milk produced/annum. For example, the quantities of zero nitrate water needed to meet the ANZG environmental and current NZDWS MAV NO₃-N limits of 0.44 and 11.3 mg NO₃-N/L, respectively, for milk production in the 2017–18 season, were determined by multiplying the grey WFs of 11,100 and 433 L/L, respectively, by 4,990,229,790 L, to yield volumes of 55.4 billion m³/annum and 2.16 billion m³/annum. The quantity of rainfall on dairy farmland in Canterbury was estimated by multiplying an assumed mean rainfall of 700mm/annum by the 360,000 ha farming area, namely a volume of 2.52 billion m³/annum.

Calculation of mean steady state nitrate concentration in groundwater from dairy farming

The mean steady state nitrate-nitrogen concentration in groundwater from dairy farming in Canterbury was estimated by assuming the mass of nitrate leached below the root zone in 2017–18 (24,393,331 kg/annum) was representative of that lost on average each year and by dividing this mass by the annual volume of groundwater in the system beneath dairy farming land (estimated above at about 1.15 billion m³/annum), yielding a mean steady state groundwater nitrate concentration in Canterbury of about 21.3 mg NO₃-N/L. We conducted a sensitivity analysis assuming that the volume of groundwater used in the steady state nitrate-nitrogen calculation was under or over estimated by 30 per cent, in addition to the nitrate leaching load for dairy production in Canterbury for the 2017–18 season being under or over estimated by 30 per cent (Etheridge et al. 2018).

Results

Dairy farming grey water footprint for the Canterbury region

Table 5 shows the grey WF of milk from farming in the Canterbury region. Of the six different standards assessed, the grey WF per litre of milk (or per kg of milk, or per kg FPCM) produced on farm using the least stringent water quality standard (11.3 mg NO₃-N/L) is 433 L. Assuming the estimated nitrate load leached per annum may be over or underestimated by as much as 30 per cent, the range for this grey WF is 303–562 L/L. Using the most stringent water quality standard, the ANZG limit for lowland waterways of 0.44 mg NO₃-N/L, the grey WF was 11,100 L per litre of milk produced, with a range
of 7770–14,400 L/L. The grey WF for one kg of milk solids product was 5620 L/kgMS using the least stringent standard, and 144,000 L/kgMS for the most stringent limit.

**Dairy farming grey water footprint for individual Canterbury farms**

The grey WFs to produce milk and milk solids were calculated for the five individual farms (Tables 6 and 7 respectively). The grey WFs were relatively consistent across the five farms; highest at farm 1 and lowest at farm 5. The mean values for the five farms was 396 L per litre of milk produced for the least stringent standard of 11.3 mg NO₃-N/L, and 10,200 L for the most stringent water quality limit of 0.44 mg NO₃-N/L. These were slightly lower than those for the entire region but within experimental error. The mean grey WFs for milk solids at the five farms ranged from 5150 L/kgMS to 132,000 L/kgMS, for the least to the most stringent water quality limits/standards respectively (Table 7).

**Significance of the milk production grey water footprint for Canterbury**

The volume of groundwater in the Canterbury system impacted by dairy farming nitrate leachate was estimated at about 1.15 billion m³/annum, equivalent to a volumetric flow of about 36.4 m³/s. Rainfall on dairy farmland in Canterbury was estimated at about 2.52 billion m³/annum, equivalent to a volumetric flow of about 79.7 m³/s.

The quantities of zero nitrate water needed to dilute the nitrate-nitrogen released below the root zone to meet the ANZG environmental and current NZDWS NO₃-N limits of 0.44 and 11.3 mg NO₃-N/L, for milk production in the 2017–18 season were estimated at 55.44 billion m³/annum and 2.161 billion m³/annum, equivalent to volumetric flows of 1758 and 68.5 m³/s for a full year, respectively. The results suggest that the volume of groundwater in the dairy farming areas (1.15 billion m³/annum) is not enough to dilute the nitrate leachate from dairy farming on average to meet the NZDWS, and even less able to meet the ANZG environmental limit. Rainwater alone falling on dairy farmland in Canterbury, if it could be all and only used for dilution purposes, would be sufficient to dilute the nitrate from dairy farming to meet the NZDWS but would provide less than a fortieth of the water required to meet the ANZG ecosystem health guideline.

**Contribution from the dairy farming grey water footprint to groundwater nitrate concentrations**

The grey WF can be used to determine what concentration of nitrate will result in a receiving water body if the volume of water in that body is known. The steady state

**Table 5.** Grey WF of milk or milk solids for the Canterbury Region for six water quality limits/standards under different nitrate load scenarios.

<table>
<thead>
<tr>
<th>Water quality limit/standard (mg NO₃-N/L)</th>
<th>Grey WF of milk (L/L, L/kg, or L/kgFPCM)</th>
<th>Grey WF of milk solids (L/kg MS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>11100 7780 14400</td>
<td>144000 101000 188000</td>
</tr>
<tr>
<td>0.87</td>
<td>5620 3930 7300</td>
<td>73000 51100 95000</td>
</tr>
<tr>
<td>1.0</td>
<td>4890 3420 6360</td>
<td>63550 44500 82600</td>
</tr>
<tr>
<td>2.1</td>
<td>2330 1630 3030</td>
<td>30300 21200 39300</td>
</tr>
<tr>
<td>2.4</td>
<td>2040 1430 2650</td>
<td>26500 18500 34400</td>
</tr>
<tr>
<td>11.3</td>
<td>433 303 562</td>
<td>5620 3940 7310</td>
</tr>
</tbody>
</table>
The grey WF values for milk production in Canterbury found in this study, both at the individual farm and regional level, were similar to those reported in another New Zealand study (Zonderland-Thomassen and Ledgard 2012), though are higher than several studies reported globally (Table 9). The grey WF for Canterbury using the World Health Organization (WHO) drinking water standard of 11.3 mg (NO₃-N/L) (World Health Organization 2011) of 433 L/L milk, the mean farm value of 396 L/L, and the individual farm grey WFs (range 310–491 L/L milk) were comparable to those reported by Zonderland-Thomassen and Ledgard (2012) for the 2004/2005 season in Canterbury (336 L/L milk), when taking into account the experimental error of about 30 per cent in the OVERSEER® estimated nutrient loss values (Etheridge et al. 2018). Zonderland-Thomassen and Ledgard (2012) found the green and blue water footprint for dairy was 748 L/L of milk. This is a substantial component of the total water footprint (green, blue and grey) when using the 11.3 mg/L water standard, but small when compared to the grey WF (11,100 L) using the most stringent environmental water quality

### Table 6. Grey WF of milk (L/L or L/kg FPCM) to reach six water quality limits/standards for five Canterbury dairy farms.

<table>
<thead>
<tr>
<th>Water quality limit/standard (mg NO₃-N/L)</th>
<th>Farm 1</th>
<th>Farm 2</th>
<th>Farm 3</th>
<th>Farm 4</th>
<th>Farm 5</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>12,600</td>
<td>9580</td>
<td>9720</td>
<td>10,980</td>
<td>7960</td>
<td>10,200</td>
</tr>
<tr>
<td>0.87</td>
<td>6370</td>
<td>4850</td>
<td>4920</td>
<td>5550</td>
<td>4030</td>
<td>5140</td>
</tr>
<tr>
<td>1</td>
<td>5540</td>
<td>4220</td>
<td>4280</td>
<td>4830</td>
<td>3500</td>
<td>4480</td>
</tr>
<tr>
<td>2.1</td>
<td>2640</td>
<td>2010</td>
<td>2040</td>
<td>2300</td>
<td>1700</td>
<td>2130</td>
</tr>
<tr>
<td>2.4</td>
<td>2310</td>
<td>1760</td>
<td>1780</td>
<td>2010</td>
<td>1460</td>
<td>1860</td>
</tr>
<tr>
<td>11.3</td>
<td>491</td>
<td>373</td>
<td>379</td>
<td>428</td>
<td>310</td>
<td>396</td>
</tr>
</tbody>
</table>

nitrate concentration in groundwater from the dairy farming grey water footprint in Canterbury on average was an estimated 21.3 mg NO₃-N/L, based on the estimated 1.15 billion m³/annum (36.4 m³/s) of groundwater in the Canterbury system impacted by dairy farming nitrate leachate. When 30 per cent errors in the estimates of the assumed nitrate load to groundwater (range 17,100–31,700 tonnes/annum) and the estimated volume of groundwater in Canterbury (range 0.803–1.49 billion m³/annum, or 25.5–47.3 m³/s) are considered, the range for the estimated mean groundwater concentration ranged from 11.5 to 39.5 mg NO₃-N/L (Table 8).

### Discussion

**Grey water footprint**

The grey WF values for milk production in Canterbury found in this study, both at the individual farm and regional level, were similar to those reported in another New Zealand study (Zonderland-Thomassen and Ledgard 2012), though are higher than several studies reported globally (Table 9). The grey WF for Canterbury using the World Health Organization (WHO) drinking water standard of 11.3 mg (NO₃-N/L) (World Health Organization 2011) of 433 L/L milk, the mean farm value of 396 L/L, and the individual farm grey WFs (range 310–491 L/L milk) were comparable to those reported by Zonderland-Thomassen and Ledgard (2012) for the 2004/2005 season in Canterbury (336 L/L milk), when taking into account the experimental error of about 30 per cent in the OVERSEER® estimated nutrient loss values (Etheridge et al. 2018). Zonderland-Thomassen and Ledgard (2012) found the green and blue water footprint for dairy was 748 L/L of milk. This is a substantial component of the total water footprint (green, blue and grey) when using the 11.3 mg/L water standard, but small when compared to the grey WF (11,100 L) using the most stringent environmental water quality

### Table 7. Grey WF of milk solids (L/kgMS) to reach six water quality limits/standards for five Canterbury dairy farms.

<table>
<thead>
<tr>
<th>Water quality limit/standard (mg NO₃-N/L)</th>
<th>Farm 1</th>
<th>Farm 2</th>
<th>Farm 3</th>
<th>Farm 4</th>
<th>Farm 5</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>164,000</td>
<td>125,000</td>
<td>126,000</td>
<td>143,000</td>
<td>103,000</td>
<td>132,000</td>
</tr>
<tr>
<td>0.87</td>
<td>82,800</td>
<td>63,100</td>
<td>64,000</td>
<td>72,100</td>
<td>52,300</td>
<td>66,800</td>
</tr>
<tr>
<td>1</td>
<td>72,000</td>
<td>54,900</td>
<td>55,600</td>
<td>62,700</td>
<td>45,500</td>
<td>58,100</td>
</tr>
<tr>
<td>2.1</td>
<td>34,300</td>
<td>26,100</td>
<td>26,500</td>
<td>29,900</td>
<td>21,700</td>
<td>27,700</td>
</tr>
<tr>
<td>2.4</td>
<td>30,000</td>
<td>22,900</td>
<td>23,200</td>
<td>26,100</td>
<td>19,000</td>
<td>24,200</td>
</tr>
<tr>
<td>11.3</td>
<td>6370</td>
<td>4860</td>
<td>4900</td>
<td>5550</td>
<td>4030</td>
<td>5150</td>
</tr>
</tbody>
</table>
standard (Table 5). These data reveal that large quantities of water are needed to produce one litre of milk on farm, but that much larger quantities are needed to dilute nitrate contamination to levels designed to maintain the health of freshwater receiving environments and ecosystems. One standout difference between the results of this and other studies is that the grey WF values can differ substantially depending on the different water quality standards used.

Most grey WF studies use the WHO nitrate drinking water standard or the USA federal drinking water standard (10 mg NO₃-N/L). A global water footprint comparison (Sultana et al. 2014) found an average grey WF for the production of a litre of energy corrected milk (ECM) of 106 L while another global study (Mekonnen and Hoekstra 2012) estimated a world average grey WF estimate of 72 litres of water for the production of a litre of milk. Making direct comparisons is difficult primarily due to the differences in measures of milk, differences in nutrients released to the environment (driven by soil type and rainfall, and on-farm practices such as stocking rate, fertiliser application and irrigation), differing and sometimes not prescribed water quality standards, and different background nitrate levels. Nevertheless, the higher grey WF calculated for dairy farming in New Zealand compared with other parts of the world likely reflects the situation where a greater degree of farm intensification is permitted and occurs in New Zealand, with a consequential much greater release of nutrients to the environment.

Outside of New Zealand, the highest grey WF was found in China (Table 9). Using modelled nitrate emissions including accounting of animal manure management, Hu

### Table 8. Estimated nitrate concentrations in groundwater from dairy farming in Canterbury in 2017–18 under different nitrate load and groundwater volume scenarios.

<table>
<thead>
<tr>
<th>Nitrate load (kg/annum)</th>
<th>Grey WF for 11.3 mg NO₃-N/L limit/standard</th>
<th>Groundwater nitrate concentrations (mg NO₃-N/L) for different annual groundwater quantities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.15 billion m³</td>
<td>1.49 billion m³</td>
</tr>
<tr>
<td>24393331</td>
<td>433</td>
<td>21.3</td>
<td>16.4</td>
</tr>
<tr>
<td>17075332</td>
<td>303</td>
<td>14.9</td>
<td>11.5</td>
</tr>
<tr>
<td>31713330</td>
<td>562</td>
<td>27.7</td>
<td>21.3</td>
</tr>
</tbody>
</table>

### Table 9. Summary of grey WF values for milk (L/milk functional unit) from water footprint-based studies.

<table>
<thead>
<tr>
<th>Water quality standard (mg NO₃-N/L)</th>
<th>Milk functional unit</th>
<th>Region/Country</th>
<th>Grey WF</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>10L</td>
<td>kg</td>
<td>India</td>
<td>63</td>
<td>Mekonnen and Hoekstra (2012)</td>
</tr>
<tr>
<td>10L</td>
<td>kg</td>
<td>Netherlands</td>
<td>25</td>
<td>Mekonnen and Hoekstra (2012)</td>
</tr>
<tr>
<td>10L</td>
<td>kg</td>
<td>USA</td>
<td>89</td>
<td>Mekonnen and Hoekstra (2012)</td>
</tr>
<tr>
<td>10L</td>
<td>kg ECM²</td>
<td>Global</td>
<td>72</td>
<td>Mekonnen and Hoekstra (2012)</td>
</tr>
<tr>
<td>10L</td>
<td>kg</td>
<td>China</td>
<td>210</td>
<td>Sultana et al. (2014)</td>
</tr>
<tr>
<td>11.3</td>
<td>kg FPCM³</td>
<td>Waikato NZ</td>
<td>268</td>
<td>Mekonnen and Hoekstra (2012)</td>
</tr>
<tr>
<td>11.3</td>
<td>kg FPCM³</td>
<td>Canterbury NZ</td>
<td>336</td>
<td>Zonderland-Thomassen and Ledgard (2012)</td>
</tr>
<tr>
<td>11.3</td>
<td>L or kg FPCM³</td>
<td>Canterbury NZ</td>
<td>433</td>
<td>This study</td>
</tr>
<tr>
<td>1.0</td>
<td>kg</td>
<td>China</td>
<td>12,616</td>
<td>Hu et al. (2018)</td>
</tr>
</tbody>
</table>

¹Assumed water quality standard as suggested by Hoekstra et al. (2011) (Table 11.6).
²ECM = energy corrected milk.
³FPCM = fat-protein-corrected milk.
et al. (2018) found an average grey WF of 12,600 L/kg of milk with a range of 1640–54,900 L. The analysis used a 1 mg TN (total nitrogen)/L water quality standard, which is the limit for Grade III Environmental Quality Standard for Surface Water in China. The results from the current Canterbury study using a similar 1 mg NO$_3^-$-N/L standard gave a grey WF of 4890 L/kg of milk, falling in the range of that of Hu et al. (2018). Thus, the results from both Hu et al. (2018), and this study, highlight the sensitivity of grey WF analyses to the variety and depth of potential data inputs, and the water standards used to determine grey WFs.

**Receiving water standards**

The water quality standard of the receiving water is crucial in determining the grey WF. The Water Footprint Network (WFN) defines the grey WF as the volume of freshwater required to dilute a pollutant so that its concentration meets the ‘prevailing water quality standards’ (Mekonnen and Hoekstra 2010; Hoekstra et al. 2011). However, what constitutes the appropriate prevailing water quality standard is equivocal and dependent on the end use of the water in question. In this study, we used a range of prevailing standards, including those used for drinking water and for protecting surface water environments. Perhaps what is most relevant to grey WF analyses then, is the contextual use of the receiving water, and the contaminant loading (and resultant grey WF) associated with each of them. In this case-study for example, the nitrate leached below the root zone from dairy farming enters groundwater. Almost all human drinking water in the region comes from groundwater, and some groundwater and surface waters are very interconnected (White et al. 2012) with some groundwater providing source water for lowland streams. Assessing the grey WF against conservative standards that are designed to protect human health within the context of drinking water is relevant, although more precautionary environmental standards might be more applicable when considering environmental impacts on groundwater ecosystems and in lowland streams.

**Drinking water standards**

For drinking water, most WFN studies use either the WHO nitrate standard, including New Zealand Ministry of Health as their Maximum Acceptable Value (MAV) for human drinking water (Ministry of Health 2018; World Health Organization 2017) or the USA standard. The WHO level was set in 1958 to protect against methemoglobinemia in infants, however, recent evidence suggests human harm can occur at much lower levels (World Health Organization 2011; Schullehner et al. 2018; Temkin et al. 2019), suggesting the need to reduce the nitrate standard. For example, epidemiological evidence has emerged that low-level nitrate contamination may be linked to colorectal cancer (CRC), thyroid disease, and neural tube defects (Ward et al. 2018). Nitrate levels one tenth of the MAV of 11.3 mg/L can significantly increase the risk of CRC in exposed populations (Temkin et al. 2019; Ward et al. 2018; Schullehner et al. 2018), with CRC, encompassing both colon and rectal cancers, the third most prevalent cancer and the second highest contributor to cancer deaths worldwide (Ferlay et al. 2020). Additionally, a recent meta-analysis found a dose–response relationship between nitrate contamination in drinking water and CRC risk, with a four per cent
increase in CRC risk per mg/L NO₃-N increase in nitrate exposure conditions (OR 1.04, 95% CI 1.01-1.07) (Temkin et al. 2019). This meta-analysis estimated elevated drinking water nitrate concentrations could be responsible for up to 8 per cent of CRC in the United States. When these thresholds are applied to New Zealand drinking water, it is estimated that between 300,000 and 700,000 individuals across New Zealand, with many in Canterbury, are exposed to drinking water nitrate-nitrogen concentrations associated with increased risk of CRC (Richards et al. 2021).

These potential links between nitrate contamination and human health have particular relevance to the case-study region. Colorectal cancer rates are very high (Shah et al. 2012) and can vary significantly in New Zealand. The highest incidences are in South Canterbury and Southland (HQSC 2020). This is particularly pertinent in Canterbury as most of the drinking water comes from groundwater and nitrate levels are already high and increasing (Tregurtha 2021). Thus, treatment of contaminated nitrate-rich drinking water may be needed in the future, or as discussed later, better farming practices with low pollutant loads may be required. While it is technologically possible to remove nitrate-nitrogen from drinking water, this is very rare globally and does not feature in New Zealand’s drinking water supply treatment processes (which focuses on removing pathogens), primarily due to difficulties treating at scale and the very high treatment costs (Sharma and Bhattacharya 2017; Bergquist et al. 2016; Rezvani et al. 2019). For example the Christchurch City Council investigated the cost of nitrate removal from drinking water to meet a 1 mg NO₃-N/L limit and found the best options would incur a one-off cost of around NZ$4000 per person and significant ongoing costs (Birdling 2020).

**Freshwater environmental standards**

Drinking water standards for nitrate contamination (e.g. the current MAV), are considerably less stringent than nitrate standards associated with deleterious effects on ecosystem health and freshwater organisms. For example, the strictest standard we analysed the grey WF against was the ANZG surface water trigger level of 0.44 mg NO₃-N/L. This is the level at which nutrients are likely to trigger excess algal growth leading to ecosystem health declines in lowland waterways (ANZG 2018). However, the recent (2020) New Zealand National Policy Statement for Freshwater Management (NPS-FM) set a national nitrate standard for surface water of 2.4 mg NO₃-N/L (Ministry for the Environment 2020) which was based on acute toxicity to aquatic life (the level toxic to one per cent of (mostly foreign) aquatic species tested in a lab setting (Hickey 2013) rather than ecosystem or human health. Significant adverse effects on life supporting capacity occur at nitrate concentrations considerably lower than those where animals start dying from toxic effects (Joy and Canning 2020).

**Significance of the milk production grey water footprint**

The grey WF for dairy farming in Canterbury can be put into perspective by determining whether there is enough zero nitrate water available to dilute the nitrate-nitrogen released below the root zone by the Canterbury dairy sector to meet different water quality limits. For example, in order to meet the ANZG environmental and current
NZDWS limits of 0.44 and 11.3 mg NO₃⁻-N/L, respectively, for milk production in the 2017-18 season (grey WFs of 11,100 and 433 L/kg, respectively), the amount of dilution water required would be 55.44 billion m³/annum and 2.161 billion m³/annum, equivalent to volumetric flows of 1758 and 68.5 m³/s for a full year, respectively. However, such large quantities of surface or ground water are not available in Canterbury to be used for this purpose.

The estimated total volume of shallow and deep groundwater available of about 1.15 billion m³/annum or 36.4 m³/s is clearly not enough to dilute the released nitrate to meet the ANZG environmental or NZDWS limits and volumes required, as outlined above. Adding surface water to groundwater in an effort to meet drinking water or environmental standards also raises some immediate issues. Much of the surface water in the region is already over-allocated; therefore little is likely to be available for managed aquifer recharge or targeted stream augmentation to dilute nitrate pollution in or from groundwater. Furthermore, it is not clear how any surface water could be injected into the groundwater, as it would need to be of sufficient quality and widely reticulated, and inserted below the root zone and into aquifers of different depths below dairy farms across the region in a timely fashion. It would also incur a significant cost. It is unclear how much water would be available and what level of dilution could be achieved, and whether other problems such as rising water tables would occur as a result.

If we assume the nitrate lost below the root zone from dairy farms in Canterbury in 2017–18 is typical and likely to be representative of what will occur annually into the future, and that the annual quantity of shallow and deep groundwater available for diluting this leached nitrate is 1.15 billion m³/annum, then in time the mean steady state nitrate concentration in the different groundwater aquifers under dairy farming land will rise to an estimated 21.3 mg NO₃⁻-N/L. The steady state concentration is one where the inputs and outputs from the system have reached a state of equilibrium, and where, for example, nitrate concentrations in the aquifers affected by dairy farming will all have reached their final steady equilibrium concentrations. It will take time for the leached nitrate to reach the various shallow and deep aquifers, and for nitrate concentrations to increase in those various aquifers and reach a steady state (this would depend on factors such as relative water quantities in different aquifers as well as how much nitrate is delivered to different aquifers). Thus the nitrate concentrations in some aquifers may rise to much higher concentrations and others may remain lower than the overall mean steady state concentration estimate of 21.3 mg NO₃⁻-N/L. This analysis of the grey WF for milk production clearly reveals that the widespread intensive dairy farming in Canterbury will lead to grossly polluted groundwater in Canterbury. As the steady state nitrate concentration estimate of 21.3 mg NO₃⁻-N/L in groundwater under dairy farms is a mean value, this will result in much groundwater exceeding the MAV of 11.3 mg NO₃⁻-N/L of the NZDWS. In addition, the situation for ecosystem health in groundwater fed lowland streams and some rivers will also be very poor.

The resulting mean steady state nitrate concentration in groundwater from dairy farming areas of about 21.3 mg NO₃⁻-N/L is consistent with the most recent data on the state of groundwater in Canterbury. Observed nitrate-nitrogen concentrations ranged between <0.002 and 22 mg NO₃⁻-N/L in the 2020 groundwater survey of 322 monitoring wells (Tregurtha 2021). Twenty wells (6 per cent) had nitrate-nitrogen concentrations above the MAV of the NZDWS. Of 249 wells, where ten-year trends in nitrate
concentrations could be estimated, 118 wells (47 per cent) showed likely or very likely increasing trends in nitrate-nitrogen, 61 wells (25 per cent) showed likely or very likely decreasing trends in nitrate-nitrogen, and 70 wells (28 per cent) showed no trend. Of the 55 monitoring wells in the Ashburton zone, which contains the greatest number of wells with elevated nitrate concentrations in Canterbury, three (5 per cent) contained nitrate levels < 1 mg NO₃-N/L, 10 (18 per cent) contained nitrate levels > 1 mg NO₃-N/L and < 5.65 mg NO₃-N/L, 29 (53 per cent) contained nitrate levels > 5.65 mg NO₃-N/L and < 11.3 mg NO₃-N/L, and 13 (24 per cent) contained nitrate levels > 11.3 mg NO₃-N/L (Tregurtha 2021). The magnitude of current well nitrate concentrations, and the greater number of wells showing increasing nitrate concentration trends, would suggest that much of the nitrate being released to groundwater by dairy farming has not yet reached a steady state in many of the different depth aquifers and monitoring wells, and that the mean steady state concentration across all depth aquifers that is expected of 21.3 mg NO₃-N/L is also yet to be reached.

This notion is consistent with nitrate concentrations found in Christchurch’s aquifers, the deep wells from which the second largest city in New Zealand and its environs source their high-quality untreated low-nitrate drinking water. All of Christchurch’s shallow, mid-depth and deep aquifers will become contaminated with nitrate from intensive farming (much of it dairy farming) permitted in the adjacent Waimakariri River catchment (Etheridge, Hansen, and Harris 2018; Kreleger and Etheridge 2019). Current median nitrate concentrations in the shallow, mid and deep aquifers of 2.5, 2.4 and 0.3 mg NO₃-N/L, will rise to about 3.7, 4.1 and 4.7 mg NO₃-N/L, respectively. Whereas nitrate concentrations have started to rise in the shallow and mid-depth aquifers in Christchurch in response to more recent land use, the same may not be the case for nitrate concentrations in the deep aquifers. The predicted steady state Christchurch aquifer nitrate concentrations are not as high as many observed in groundwater to the south of Christchurch in the Ashburton zone, as river water from the Waimakariri River system significantly dilutes nitrate leached from an interzone source transfer area from which nitrate passes into groundwater that flows into the Christchurch aquifers (Kreleger and Etheridge 2019). Based on epidemiological research and short- and long-term monitoring data then, the increasing trend of nitrate contamination in Canterbury drinking water could pose a serious and direct threat to human health.

**Sustainability of dairy farming in Canterbury and the international situation**

Although it is a widely held belief that New Zealand dairy farming is the most efficient and environmentally sustainable in the world, this is not true. The OECD definition of sustainable farming is that which is economically viable and results in no long-term environmental degradation. Dairy farming as it is practised and permitted in Canterbury is causing significant long-term environmental degradation because of its grey WF and is not sustainable, considering the problems similar farming has caused throughout the world (Bos et al. 2005). Unless nitrate leaching from such farming practices is greatly reduced, it will continue to cause excessive nitrate concentrations and environmental harm in groundwater, lowland streams and a number of rivers and lakes throughout New Zealand. A reduction in nitrate leaching could be achieved by adopting alternative low nutrient-release farming strategies, such as herd shed farming and/or halting direct
cattle urination onto pasture, and spreading all farming effluent uniformly over land so that the nitrate it contains can all be re-utilised in pasture or crop growth and not end up in groundwater, reducing irrigation, and locating dairy farms on soils with low or no nitrate leaching potential.

If the ANZG 0.44 mg NO₃-N/L environmental standard for lowland rivers was adopted as a precautionary proxy for protecting groundwater ecosystems including stygobiota in the absence of established standards, because stygobiota are considered more fragile than their surface water terrestrial counterparts (EMA 2018; Fenwick et al. 2018), very large reductions in nutrient leaching would be required. For example, reductions of 96.1%, 97.9% or 98.6% are needed to reduce groundwater nitrate concentrations currently at the drinking water standard of 11.3 mg NO₃-N/L, at the mean steady state concentration of 21.3 mg NO₃-N/L, or at a higher possible concentration of 31.3 mg NO₃-N/L, respectively, to those of the ANZG 0.44 mg NO₃-N/L environmental standard. Twenty per cent reductions in nutrient release over the next ten years are required to meet consent conditions in the recently re-granted resource consent for river water abstraction for irrigation in the large Mayfield-Hinds-Valetta Irrigation scheme in the Ashburton zone (McGarry 2021). However, this will do little to rectify rising groundwater concentrations and poor health of groundwater and associated surface water in the area, and risks to human health from groundwater used for drinking water in the zone, and especially if nitrate standards for drinking water are lowered. As an example, a 20 per cent reduction in nutrient release would reduce the groundwater concentrations from 11.3, 21.3 and 31.3 mg NO₃-N/L to 9.04, 17.0 and 25.0 mg NO₃-N/L, respectively. A further 95.1%, 97.4% or 98.2% reductions in nutrient release, respectively, would be needed to meet the ANZG 0.44 mg NO₃-N/L environmental standard.

The issues highlighted in this study are a microcosm of the international situation resulting from the industrialisation of agriculture. The European Science Foundation has declared that industrial production of reactive nitrogen ‘represents perhaps the greatest single experiment in global geo-engineering that humans have ever made’ (Sutton et al. 2011). Intensiﬁcation of agricultural systems, of which synthetic nitrogen fertiliser is a big part, is justified in the face of a growing global population and increasing food insecurity. Trade-offs between environmental impacts, human health, and the immediate need for increased food production are seemingly warranted given the current structure of globalised food production and distribution. Intensiﬁcation without accurate accounting of production externalities, however, misrepresents current food production costs, with many of the impacts of such imbalances now ubiquitous (Foote, Joy, and Death 2015). As populations continue to increase, and demand for protein-rich, calorie dense products also increase, accurate accounting of associated food production costs will be critical not only to mitigate human and environmental health risks, but to meet shifting consumer demands for sustainable products (Errickson, Kuruc, and McFadden 2021; Crippa et al. 2021).

Annual global milk consumption has increased 2.7 times between 1961 and 2013, from 230 million tonnes to 630 million tonnes (FAO 2018). With intensiﬁcation ongoing globally to meet this demand, the extremely high grey WF for milk production we revealed is one component among a suite of environment impacts of intensive agriculture, that ranges from the spread of zoonotic pathogens to high levels of pesticides, to ongoing habitat loss and greenhouse gas emissions (Phiri et al. 2020; Hageman et al. 2019). With the developing knowledge regarding the direct human health risks
associated with nutrient contamination, accurate accounting and greater transparency around where food comes from and how it is produced is needed (Hoekstra 2012).

In Canterbury the amount of nitrate leached to the environment more than doubled from 1990 to 2017 (Ministry for the Environment and Statistics New Zealand 2019). The average for dairy stocking rate for New Zealand in 2017-18 was 2.8 cows per hectares and for Canterbury 3.4 cows per hectare (LIC and DairyNZ 2018). This stocking rate is high compared to the rate of about one dairy cow per ha mandated by the European Union (EU) to protect freshwaters. EU member states are required to guarantee that the annual farm application of nitrogen, as animal manure, does not exceed 170 kg per hectare, equivalent to a stocking rate of one cow per ha (Mateo-Sagasta, Zadeh, and Turrall 2018).

**Conclusion**

Using water footprinting we quantified the grey WF for nitrate leaching into groundwater from milk production in Canterbury, New Zealand. Our analyses show similar results to previous grey WF estimates from dairy farming in New Zealand, and that grey WF analyses in general are highly sensitive to the water standards against which they are assessed. The grey WF for milk production on farm, and observed nitrate concentrations in monitoring wells, clearly reveal that the widespread pasture-based intensive dairy farming in Canterbury is unsustainable and is leading to grossly polluted groundwater in Canterbury and serious environmental degradation. Dairy farming will result in steady state nitrate concentrations on average of 21.3 mg NO$_3$–N/L in groundwater originating from dairy farming areas in Canterbury, rendering much of it undrinkable. The groundwater drinking water supply of Christchurch, the second largest city in New Zealand, will also become significantly polluted with nitrate from dairy farming in the Waimakariri River catchment, and the current deep aquifer median nitrate concentrations of 0.3 mg NO$_3$–N/L will rise to median concentrations of at least 4.7 mg NO$_3$–N/L. Very large reductions of nutrient leaching of the order of 96 per cent are needed to reduce elevated groundwater nitrate concentrations, for example, such as those currently at the drinking water standard of 11.3 mg NO$_3$–N/L to those of the ANZG 0.44 mg NO$_3$–N/L environmental standard that could be a proxy standard for retaining healthy groundwater ecosystems. Unless this environmental degradation is reversed and current dairy farming significantly reduced and/or replaced by low-nitrate emission non-pasture grazed systems, dairy farming on the Canterbury Plains will remain unsustainable and seriously damaging to the local freshwater environment, including local drinking water sources. This degradation could continue to pose a significant human health risk and threat to our global market for dairy products.

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