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New Zealand Dairy Farming: Milking Our Environment for All Its Worth

Kyleisha J. Foote[1] · **Michael K. Joy**[1] · **Russell G. Death**[1]

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Abstract Over the past two decades there have been major increases in dairy production in New Zealand. This increase in intensity has required increased use of external inputs, in particular fertilizer, feed, and water. Intensified dairy farming thus incurs considerable environmental externalities: impacts that are not paid for directly by the dairy farmer. These externalities are left for the wider New Zealand populace to deal with, both economically and environmentally. This is counter-intuitive given the dairy industry itself relies on a 'clean green' image to maximize returns. This is the first nationwide assessment of some of the environmental costs of the recent increase of dairy intensification in New Zealand. Significant costs arise from nitrate contamination of drinking water, nutrient pollution to lakes, soil compaction, and greenhouse gas emissions. At the higher end, the estimated cost of some environmental externalities surpasses the 2012 dairy export revenue of NZ$11.6 billion and almost reaches the combined export revenue and dairy's contribution to Gross Domestic Product in 2010 of NZ$5 billion. For the dairy industry to accurately report on its profitability and maintain its sustainable marketing label, these external costs should be reported. This assessment is in fact extremely conservative as many impacts have not been valued, thus, the total negative external impact of intensified dairying is probably grossly underestimated.

Keywords Externalities · Intensification · Environmental impacts · Cattle · Water quality · Dairy industry

Introduction

New Zealand dairy farming has intensified and expanded dramatically in the past two decades. Meanwhile, production declines have occurred in other pastoral agricultural sectors, such as sheep and beef farming. Intensification can be defined as an increase in outputs per unit area (MacLeod and Moller 2006; Moller et al. 2008), by increasing inputs (Beukes et al. 2012). Dairy intensification has increased the need for external inputs to enable higher stocking rates and production increases. This intensification has been associated with environmental effects that are external to the farm, termed externalities.

Most economic activities have an impact on the environment, either by extracting resources from the environment or disposing wastes back into the environment, or both (Pretty et al. 2000; Prugh et al. 1999; Turner et al. 1994). Humans have invaded every ecosystem on Earth's surface and many human enterprises exploit their resource base, including agriculture, industry, fishing, and commerce (Vitousek et al. 1997). Rockström et al. (2009) propose that humanity has already exceeded three planetary boundaries out of the seven they quantified for global sustainability. While there is an increased awareness of environmental issues and the need to account for them in policy, environmental degradation continues to accelerate (Ekins et al. 2003). Moreover, the current dominant economic system of valuation [using Gross Domestic Product (GDP)] does not adequately incorporate the costs of environmental impacts or the true value of natural resources and services (Bertram 2013; Costanza et al. 1997; Daily

✉ Kyleisha J. Foote
kyleisha_foote@yahoo.co.nz

[1] Institute of Agriculture and Environment - Ecology Group, Massey University, Private Bag 11-222, Palmerston North 4442, New Zealand

et al. 1997; Daly 2005); hence costs are externalized (Pretty et al. 2000). This results in market prices being distorted as the true costs of production are understated (Hackett 1998; Pretty et al. 2000), leading to overproduction and overconsumption. Externalizing costs encourages activities that are damaging to society, even if they result in considerable private benefits (Pretty et al. 2000). The producer of the negative environmental externality is receiving an implicit subsidy of the amount that would otherwise be spent on pollution control (Templet 1995).

Externalities generally affect the utility or wellbeing of a third party (the public) who are uncompensated by the producer of the effect (Perman et al. 1996; Pretty et al. 2000; Turner et al. 1994). Thus, the public is left to deal with the costs of the effects, whether these involve, for example, the cost of cleaning up pollution or the cost of having a degraded environment. Costs are in the form of government remediation funded by public taxes (Abell et al. 2011), public health costs associated with an unhealthy environment or contamination, and the loss of income from tourism, among many others. In this way, the public is indirectly subsidizing polluters by paying for the costs of pollution. New Zealand is not exempt from this process and the dairy industry is a classic example of unaccounted for externalities left for the general public to pay. The dairy industry does not pay for all its environmental pollution and the growth of dairy farming has occurred with little balanced economic evaluation or even awareness of the true environmental impacts and costs. This study identified some of the environmental impacts and externalities produced from the New Zealand dairy industry and the costs associated with mitigating these.

Trends in Dairy Production and Inputs

Primary production is New Zealand's main export earner; dairy products contributed 25 % of New Zealand's export revenue in 2012, rising from 13 % in 1990. Dairy exports increased in value by 460 % over this time, from $2 to $11.6 billion (Statistics New Zealand 2012). In 2010, the dairy sector directly accounted for 2.8 % of GDP, or $5 billion (Schilling et al. 2010), although this has probably increased since then. Thus, dairy's total contribution (approx. NZ$16.6 billion) is undoubtedly higher than any other sector in New Zealand. Land in dairying increased by 46 % from 1993 to 2012 (reaching around 2.4 million ha in 2012), while dairy cattle numbers almost doubled from 1990 to 2012, from 3.4 million to nearly 6.5 million (Statistics New Zealand 2012). From 1990 to 2012, the number of dairy herds decreased by 19 %, while the average herd size expanded by 147 %. During this period, milksolid (MS) production increased by 195 %, from 0.572 to 1.685 million tonnes (LIC and DairyNZ 2012). MS production per cow and per hectare increased 40 and 60 %, respectively, between 1993 and 2012 (LIC and DairyNZ 2012). Major dairy farming regions in New Zealand are outlined in Fig. 1.

External inputs are required to increase dairy production to this level, such as fertilizer, brought-in feed sources, and water. Major imported products used in the dairy industry that can be traced are palm kernel expeller (used for feed), and fertilizers. Imported products carry their own environmental implications from extraction and manufacturing in their country of origin, for example, conversion of indigenous rainforest to palm plantation (from which palm kernel is obtained), that are not considered in this analysis of the New Zealand dairy farming system.

Fertilizers

As farming intensifies, more nutrients are added to increase production and compensate for losses, depending on the soil type, crop species, and nutrient loss—to the environment and in agricultural products (Beukes et al. 2012; Parliamentary Commissioner for the Environment 2004; Powell et al. 2010). Fertilizers commonly used in New Zealand include lime; phosphatic (P) fertilizers such as Superphosphate; nitrogenous (N) fertilizers such as urea and ammonium sulfate; potassic (K) fertilizers; and compound fertilizers containing more than one nutrient, for example, di-ammonium phosphate (DAP) (Roberts and Morton 2009; Statistics New Zealand 2006). The cost of imported fertilizers for dairy farming was estimated using the proportion of each fertilizer used on dairy farms [around 70 % of nitrogen and 34 % of phosphorus (Statistics New Zealand 2013a)], equalling around NZ$503 million in 2012.

The main nitrogen fertilizer used in New Zealand is urea with major increases in use since the 1980s. The dairy industry increased its urea use by 360 % between 1996 and 2012 and used 72 % of the total in 2012 (Statistics New Zealand 1998, 2013a). New Zealand produces approximately 260,000 tonnes of urea annually using natural gas. More than double this amount was imported in 2012 (526,000 tonnes) with 80 % from Saudi Arabia and Qatar (Statistics New Zealand 2013b).

Global demand for phosphorus is dramatically increasing as fertilizers are used more (Rosemarin et al. 2009), primarily for industrialized agriculture (Ashley et al. 2011). Phosphate rock is a non-renewable resource that takes 10–15 million years to cycle naturally (Cordell et al. 2009), and unlike nitrogen, there is no synthetic alternative. In 2012, 34 % of superphosphate in New Zealand was used on dairy farms (Statistics New Zealand 2013a).

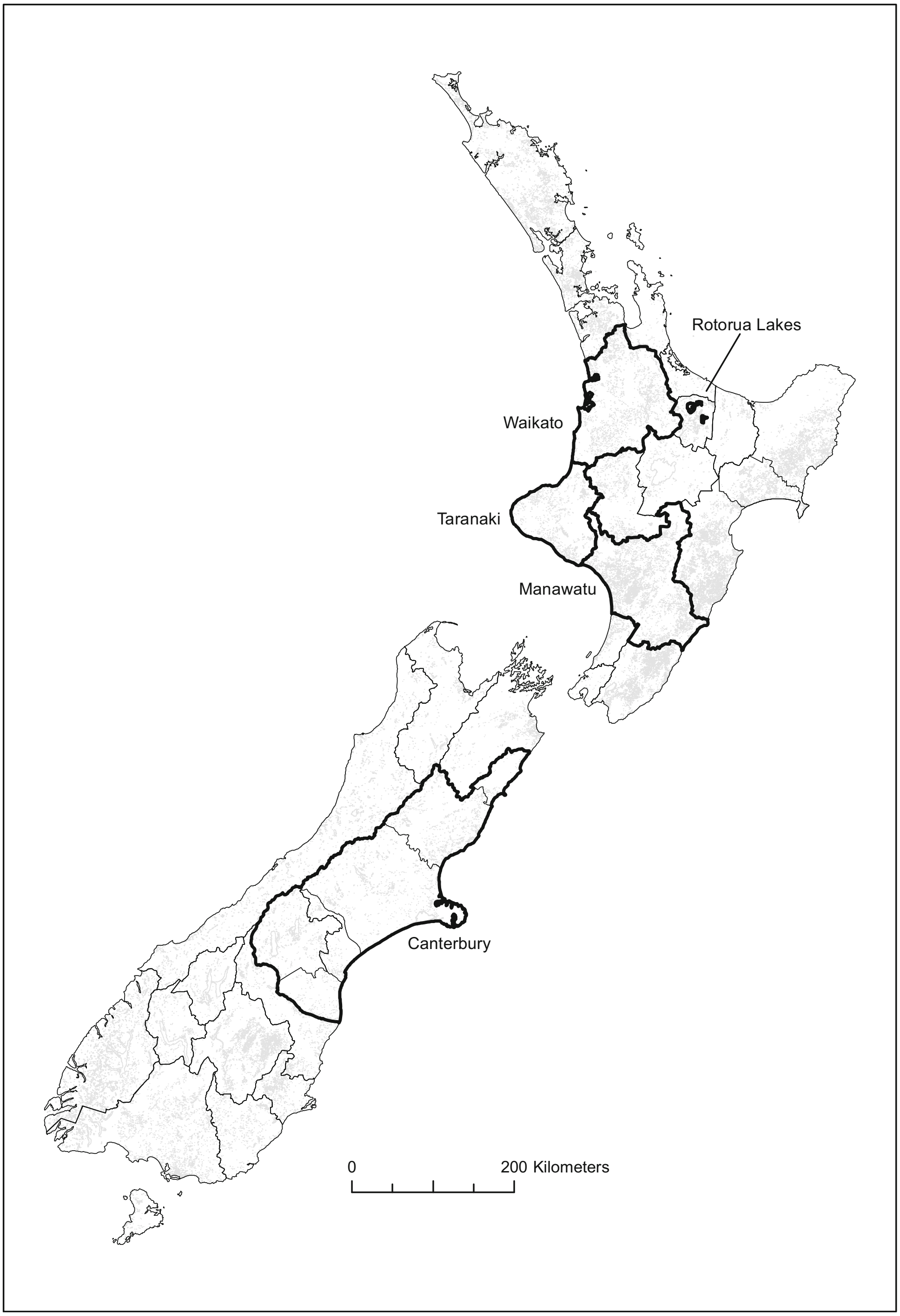

Fig. 1 Map showing the major dairy farming regions in New Zealand (*dark outlines*) and location of the Rotorua Lakes

Brought-in Feed

Intensification also requires feed to be brought in which is now used by about 85–90 % of dairy farms (DairyNZ 2013) with the purpose of grazing cows off the milking area and/or extending lactation periods and increasing stocking rates. A particularly important feed supplement is palm kernel expeller (PKE), a product left after oil extraction from the palm seeds of oil palm. The production of palm oil generates environmental impacts outside New Zealand, including deforestation, biodiversity loss, and greenhouse gas (GHG) emissions. New Zealand is the largest global importer of PKE, importing 30 % of the total global trade in 2012 (Index Mundi 2012), all used for dairy feed. Imports of PKE into New Zealand have increased substantially from virtually nothing in 1992 to nearly 1.4 million tonnes in 2012 (costing NZ$274 million in 2012) (Statistics New Zealand 2013b).

Measuring Externalities

Several attempts have been made to put a price on some forms of pollution from agriculture in New Zealand, particularly on water quality. For instance, the NIWA Waikato River Independent Scoping Study (WRISS) (NIWA 2010b) prices the cost to clean up the Waikato River to a standard determined by a co-management agreement. Examples of costs to remove nutrients from lakes have also been provided from projects in the Rotorua Lakes (Abell et al. 2011; Environment Bay of Plenty et al. 2006; Hamill et al. 2010).

Several studies have measured peoples' stated preference to improve water quality or reduce pollution in selected agricultural catchments. These studies do not price the true value of natural resources and ecosystem services or the cost of cleaning up, but the perceived value communities place on these resources and are termed non-market valuation (NMV) methods. Although this type of research is helpful in seeking community opinions, NMV techniques may severely underestimate the true value of nature because many people lack the knowledge of the worth of natural resources and ecosystem services. Additionally, NMV tools cannot value all parts of a natural resource (Awatere 2005), may undervalue the cost of environmental degradation, and may not accurately measure financial costs. Life cycle analysis (LCA) is another tool that aims to measure the total environmental effects of a product from resource extraction to disposal ("cradle to grave"), taking into account the use of natural resources (such as clean water) and disposal back into the environment of degraded resources. Using LCA to measure environmental impacts across an entire industry involves averaging data from many different sources and fails to account for the variability of environmental burdens (Duda and Shaw 1997). Additionally, it is very data intensive and requires information on all aspects of a product life cycle which was not available for this study.

Despite dairy being New Zealand's predominant export industry, there has been no national level analysis on the environmental impacts and costs of dairy farming in New Zealand. Tait and Cullen (2006) priced some external costs of dairy farming in Canterbury over four cost categories on the damage to: water resources, air resources, ecosystem biodiversity, and human health. This appears to be the most comprehensive economic analysis of dairy impacts in New Zealand. Quantifying the environmental impacts of dairying is challenging, both in monetary and ecological terms. It is difficult to value non-market goods—things that are not included in the formal economy (e.g., GDP), because there are no markets where they are regularly brought and sold, and hence their market price cannot be easily determined (NIWA 2010a). There is a need to accurately measure the financial cost of impacts, i.e., what it actually costs to remedy or mitigate impacts.

The external costs of agriculture have been measured in other areas of the world. For example, Pretty et al. (2000) assessed the total external costs of agriculture in the UK, including both derived environmental and human health impacts. Total annual costs in 1996 were £2343 million, equivalent to £208/ha of arable and permanent pasture (Pretty et al. 2000). Tegtmeier and Duffy (2004) estimated external costs of agricultural production in the United States at US$5.7 to $16.9 billion annually, equivalent to US$29.44 to $95.68 (£16.87 to £54.82) per hectare of cropland. Environmental and social costs from pesticide use in the US totalled approximately US$10 billion annually (Pimentel 2005). In New Zealand, Tait and Cullen (2006) calculated external costs of dairy farming in Canterbury at NZ$169.59 to $308.23 per hectare.

In this study, we included economic measures relating to dairy impacts of the cost to remove nitrogen from water exceeding drinking standards; the cost to remove nutrients from lakes; the cost to remedy soil compaction; the potential price of a tax on GHG emissions; and the potential loss of dairy export revenue from degradation of New Zealand's 'clean green image'. Although these are not all actual costs presently, some costs may represent the price if polluters were required to pay for their external pollution via a tax (i.e., GHG emissions), or may fall on society in the way of subsidies provided to the industry (either directly or indirectly). These measures are small in comparison to the wide ranging effects from dairy farming, but can provide a starting point in the analysis of costing dairy impacts.

Environmental Impacts and Cost Analysis

Agricultural intensification, even if managed carefully, contributes to environmental deterioration (Allan 2004). Impacts damage New Zealand's 'clean green' image, threaten future food production, and lead to biodiversity loss and degradation of recreational areas. Costly and challenging remediation solutions are often needed because pollution is not reduced at the source. Yet, the costs of mitigation options to reduce the adverse impacts associated with dairy farming have rarely been evaluated. Thus, many of the impacts remain un-valued (or under-valued). Costs are involved with: remedying impacts, environmental degradation, and legitimizing environmental externalities that are largely publically subsidized. Collectively, more cost-effective solutions may involve management practices to minimize the impacts in the first place, rather than paying for expensive clean-up projects after pollution occurs. Only a small number of the environmental impacts have been economically valued thus far and the range of costs provided here is based on an average approximation of the environmental impact analyzed in most cases. Even given these limitations, our investigation reveals an indication of the costly remediation practices New Zealand could be facing. This study did not aim to compare costs with a reference level or another land use but only considered externalities from dairy farming. Further analysis is needed to compare alternate land uses that may be economically advantageous and/or environmentally sustainable.

Freshwater Impacts

Water quality in New Zealand pastoral catchments is on a declining trend, driven by agricultural intensification (Ballantine and Davies-Colley 2009; Cullen et al. 2006; Larned et al. 2004; Parliamentary Commissioner for the Environment 2004). Rivers and streams in agricultural or urban catchments generally have poorer water quality than those with little or no farming and urban development (Larned et al. 2005; Ledgard et al. 1996; Ministry for the Environment 2007a; Rodda et al. 1999). Dairying has been shown to have a disproportionate effect on that decline in water quality compared to other agricultural practices (Davies-Colley and Nagels 2002; Ministry for the Environment 2009; Townsend et al. 1997). Intensive dairying practices that impact freshwater include: water abstraction, increased stocking rates, riparian grazing, fertilizer application, vegetation removal, and wetland drainage. These lead to an increase of fecal contamination, excess nutrients, and sedimentation in water (Ledgard et al. 1996; Willis 2001).

Human health effects in waterways from dairy farming pollutants are derived from fecal matter and nitrate (NO_3). One dairy cow is estimated to excrete fecal bacteria equivalent to about 14 people (Environment Waikato 2008), representing nationwide values equivalent to over 90 million people. The presence of fecal matter in freshwater is revealed by measuring fecal indicators, such as fecal coliforms and *Escherichia coli* (Davies-Colley et al. 2003). *E. coli* concentrations frequently exceed guidelines for contact recreation in pastoral catchments and are typically between two and 20 times higher than those in forested catchments (Davies-Colley et al. 2004; Larned et al. 2004). Larned et al. (2004) found that 96 % of 259 pastoral sites from 1998 to 2000 exceeded *E. coli* guidelines for contact recreation. Water contaminated with fecal pathogens affects recreational uses, drinking water quality (Davies-Colley et al. 2003; Ministry for the Environment 2009; Parliamentary Commissioner for the Environment 2004), and shellfish (Collins et al. 2007; Donnison and Ross 1999). Contaminated water can also affect livestock, causing reduced growth, morbidity, or mortality (Smith et al. 1993). In New Zealand there are between 18,000 and 34,000 cases per annum of waterborne gastro-intestinal diseases from contaminated water, although this is likely to be an underestimate because many cases are unreported or undiagnosed (Ball 2006). It is difficult to determine the source of waterborne diseases and the costs involved in treating them. Consequently, costs of fecal contamination from dairy farms were not determined.

Estimated nitrogen (N) leaching rates from dairy farms nationwide ranged from around 12–200 kg N/ha/y, depending on soil type, amount of fertilizer applied, source and quantity of supplementary feed, stocking rate, and irrigation use. OVERSEER® (a nutrient budget computer model) estimated average N leaching on dairy land of 28 kg N/ha/y, while the New Zealand average from agricultural land (including dairy land) was 8 kg N/ha/y (Ledgard et al. 2000). Leaching rates on irrigated dairy farms in Canterbury have been recorded as high as 180 kg N/ha/y (Lilburne et al. 2010), while in the Manawatu/Whanganui region, losses are estimated at 15–115 kg N/ha/y (Dewes 2012). Dairying contributes a disparate amount of nutrients to freshwater than other land uses. In the upper Manawatu catchment, dairy farms contribute around half of the nutrient load from approximately 17 % of the catchment (Dewes 2012); in the Waikato region, dairying is responsible for 68 % of the nitrogen and 42 % of phosphorus entering waterways from 22 % of the land area (Environment Waikato 2008). Elliott et al. (2005) estimated that dairy land (covering 6.8 % of land area nationwide) accounted for almost 40 % of total nitrogen loads to streams, the same proportion as the combined loads from other pastoral areas covering 32 % of land (sheep and beef farming). Livestock urine is the largest source of nitrogen leaching from dairy farms, accounting for as much as 90 % of total N leaching (Davies-Colley et al. 2003; de Klein and Ledgard 2001; Ledgard et al. 2009). Furthermore, although water quality management is largely focused on point sources, data showed only 3 % of nitrogen and 7 % of phosphorus were derived from point sources in the Waikato region (Environment Waikato 2008), posing critical questions relating to policies and rules around the management of freshwater.

As a result of these high leaching rates, elevated NO_3 levels are found in many shallow groundwater aquifers (down to 60 m), especially below dairy land in highly stocked areas (Ministry for the Environment 2007b; Parliamentary Commissioner for the Environment 2004). The Ministry of Health’s (MoH) Maximum Acceptable Value

(MAV) in drinking water is 50 mg/L NO_3 (Ministry of Health 2008), equivalent to 11.3 mg/L nitrogen as nitrate-N (NO_3-N) (Cassells and Meister 2000; Ford and Taylor 2006). In 2008, around 30 % of groundwater sites under dairy land in Waikato did not meet the MoH drinking water guidelines, compared with only 5 % from drystock farms and urban wells (Environment Waikato 2008). Likewise, groundwater testing in the 1980s on Taranaki dairy farms showed that over 40 % exceeded these standards (Ledgard et al. 1996). Testing in Canterbury groundwater wells in 2012 showed 11 % of tested wells did not meet the drinking standards (Environment Canterbury 2013b), up from 7 % in 2011 (Environment Canterbury 2013a). Elevated NO_3 levels in groundwater are an issue because about 40 % of New Zealand's population relies on groundwater for drinking (Rajanayaka et al. 2010). Excessive nitrogen ingestion can lead to certain types of cancers and has been linked with methemoglobinemia, a blood disease in infants also known as the blue baby syndrome[1] (Ministry for the Environment 2007a; Parliamentary Commissioner for the Environment 2004). Conversely, Addiscott and Benjamin (2004) claim that methemoglobinemia is caused by nitric oxide, not by NO_3, and that high NO_3 concentrations in water do not threaten human health (i.e., are not linked with methemoglobinemia). Their study suggests evidence is inconclusive for the current NO_3 standards in water to protect human health and that NO_3 may in fact be beneficial for health by protecting against organisms that cause gastroenteritis and fungal pathogens. Regardless of discrepancies, ecological effects occur at much lower NO_3 levels than drinking standards, acknowledged by Addiscott and Benjamin (2004), so it would be beneficial to manage water to protect ecological integrity.

To determine the potential cost of NO_3 leaching, it may be reasonable to estimate the cost of treating contaminated water for drinking as the public drinking water supply must meet the MoH NO_3 standards. Leaching of 1 kg of NO_3N from soil will contaminate about 88.5 m^3 of water from 0 mg NO_3N/L to 11.3 mg NO_3N/L: the MAV for drinking water. To reduce NO_3 concentrations by 85–95 % in water costs on average between NZ\$0.30 and \$1.80 (2013 conversion rates) per 1000 L (Jensen et al. 2012). However, costs are scale dependant; they vary considerably between system types and volume of water treated and can be much higher (around \$5.00/1000 L) (Jensen et al. 2012). New Zealand cost estimates are not readily available possibly because NO_3 currently does not reach levels high enough in public drinking water sources. However, treatment may be required in the future as NO_3 levels increase; therefore, these treatment costs have been estimated and included.

Using the average dairy leaching rate of 28 kg N/ha/y, the volume of water estimated to reach the MAV for drinking water (from zero NO_3 levels) from dairying land (about 2.4 million ha) is 5947 million cubic meters (Mm^3). Removal of this NO_3 is estimated to cost between \$1.78 and \$10.7 billion. In reality, all of the contaminated water would not be used for drinking. Nevertheless, it represents a degraded natural resource and an externality of dairy farming. Additionally, these estimates are based on water initially containing no NO_3; however, many groundwater reservoirs already contain NO_3 with some areas currently exceeding drinking water standards.

Ecological effects in surface water have been shown to occur at NO_3 levels lower than 1 mg/L (Davies-Colley 2000). Excessive levels of nitrogen and phosphorus increase plant growth, and can cause algal blooms and an over-abundance of aquatic weeds, leading to eutrophication (enhanced phytoplankton and periphyton growth) (Marsh 2012; Smith et al. 1993; Tilman 1999). Eutrophication causes fluctuating oxygen levels in water (can be harmful and deadly for fish), as well as poor water clarity, rending water bodies unsuitable for swimming and degrading esthetics (Smith et al. 1993).

Agricultural streams are often degraded from wide diurnal changes in pH, temperature and dissolved oxygen (DO), and poor visual clarity (Davies-Colley and Nagels 2002; Wilcock et al. 2007; Wilcock et al. 1999). Continuous monitoring of pH, temperature, and DO in dairy streams have revealed extreme values not normally observed when parameters are measured once or twice a day (Wilcock et al. 2007). Minimum DO levels measured in five dairy catchments were almost all below the guideline for the protection of aquatic ecosystems, fisheries, and fish spawning of >80 % saturation; healthy ranges for biodiversity are between 98 and 105 % saturation (Wilcock et al. 2007). In autumn, DO levels for the Toenepi Stream, Waikato (predominantly in dairy) were all below 40 % saturation and some levels were less than 10 % DO (Wilcock et al. 2007).

Additionally, many shallow lakes in New Zealand are nutrient enriched (eutrophic) (Smith et al. 1993), mostly in lowland pasture dominated catchments in the North Island (Parliamentary Commissioner for the Environment 2004; Verburg et al. 2010). Forty-four per cent of monitored lakes in New Zealand (or 84 % of lakes in pastoral catchments) are in a eutrophic state or worse (Verburg et al. 2010). Monitoring found that half of the lakes in pastoral land had poor ecological condition and bottom water oxygen concentrations decreased significantly with increased percentage of pastoral land cover (Verburg et al. 2010).

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[1] High levels of nitrite in the blood can cause higher than normal levels of methemoglobin which has a decreased ability to bind oxygen. 'Blue-baby syndrome' occurs when methemoglobain levels in the blood are so high that the skin turns a bluish color and is more common in infants.

A range of actions have been implemented to reduce nutrient loads from internal (lake bed sediments) and external (land use) sources in the Rotorua Lakes (see Fig. 1 for location). Costs for the removal of nitrogen from the Lakes using constructed floating wetlands range from NZ$14,000/tonne N (Hamill et al. 2010) to $4 million/tonne N and around $250,000/tonne P (Ford-Robertson 2013). Dairy farming in four of the Rotorua lake catchments is estimated to leach around 320 tonnes N per year and 4.5 tonnes P per year, yielding a cost between NZ$4.48 million and $1.28 billion for N and NZ$1.125 million for P.

On-farm reduction of nutrients may be cheaper than removing nutrients once they reach wider ecosystems. For example, cutting N fertilizer on six dairy farms in the Rotorua catchment was estimated to reduce returns by $46–$428/ha/y and the average loss in gross revenue per ha was $173 (Ledgard et al. 2010). The resulting average reduction in N leaching over the six farms was 26 kg N/ha/y (Ledgard et al. 2010), yielding a reduction in gross margin of $6.62/kg N or $6620/tonne N. Thus, removing N from the Rotorua lakes (using constructed floating wetlands in the example above) was 2–600 times more costly than reducing N inputs in the first place.

Impacts on Soil

Intensification of dairy farming has direct impacts on soil affecting potential future land uses. Fertilizers and other agricultural chemicals applied to dairy land often contain heavy metals that can accumulate to high levels in soil, risking the potential to export produce and grow certain crops. Overstocking cows and using heavy machinery can lead to soil compaction, having severe physical impacts on soil that may limit production and increase runoff. Organic matter, fertility, acidity, and physical condition are often used to determine soil quality. New Zealand nationwide soil assessments found around 70 % of monitored sites did not meet at least one of the soil quality targets, with the main concerns being compaction, excess nutrients and depleted organic matter (Sparling and Schipper 2004). These issues will affect production and may contribute to eutrophication of receiving waters. Sampling in the Waikato region in 2009 revealed over 80 % of dairy pasture sites not meeting at least one soil quality target, and over 30 % failing to meet two or more targets (Taylor 2011). Dairy and other pastoral land uses had the lowest proportion of sites that met soil targets, both in the Waikato (Taylor 2011) and nationwide (Ministry for the Environment 2010).

Soil Compaction

Compaction occurs when soil cannot support the weight forced upon it (Ledgard et al. 1996), and intensifies when soils are wetter, at higher stocking rates, and when animals are grazed during long winter rotations (Ledgard et al. 1996; Mackay 2008; Russell et al. 2001; Sparling and Schipper 2004). Compaction reduces plant cover, exposes soils, and affects soil physical properties (Ledgard et al. 1996; Nguyen et al. 1998; Pande 2002), associated with a reduction in the amount of macropores (air pockets) in soil (Mackay 2008). The resulting reduction in water storage (Drewry 2006; Russell et al. 2001) can lead to increased runoff into surface waters, soil erosion (Ledgard et al. 1996; Nguyen et al. 1998; Pande 2002), and surface ponding of water on land (Mackay 2008). Damaged soil structure restricts root growth and nutrient uptake by plants, negatively affecting plant productivity (Ledgard et al. 1996, 2009; Mackay 2008; Menneer et al. 2001). Additionally, compaction can increase GHG emissions emitted from soils (Ledgard et al. 1996). Compaction may be the most significant soil quality issue in the Waikato region and land under dairy pasture is the most significantly affected (Taylor 2011). On half the dairying sites they tested in New Zealand, Sparling and Schipper (2004) found a macroporosity (measure of compaction) of less than 10 %: rates at which pasture production can be adversely affected. This was lower than sites under arable cropping land and drystock pasture. Likewise, the Ministry of the Environment (2011) reported that 53 % of dairy sites failed to meet macroporosity targets, while Taylor (2011) reported 37 % of tested Waikato dairy sites failed macroporosity targets in 2009 (the highest proportion under any land use), decreasing from 70 % in 2003.

Thorrold (2000) reviewed the costs of pasture damage from compaction on a typical Southland farm from a 10 % decrease in yield over the farm. Remediation costs depended on whether the feed was replaced or if production reduced but ranged between NZ$84 and $480 per ha. By extrapolating this to a national scale, compaction costs on dairy land were estimated at NZ$75 million to over $600 million (Table 1). These costs only account for remediation of pasture production and not the resulting impacts on the wider environment, for example, on flooding, increased runoff of contaminants, and increased GHG emissions, because these impacts are difficult to quantify.

Greenhouse Gas Emissions

New Zealand's per-capita GHG emissions in 2012, at 18.72 tonnes carbon dioxide equivalents (CO_2-e) per person, were 24th highest in the world and 5th in the OECD (World Resource Institute 2013). Almost half of New Zealand's GHG emissions are derived from agriculture (mainly methane and nitrous oxide) and about a quarter from dairy farming. Methane is produced by the digestive processes (enteric fermentation) of ruminant animals and

Table 1 Estimated cost of compaction damage for national dairy farming area

Action[a]	Cost (NZ $million)	
	37 % land effected[b]	53 % land effected[c]
Replacing feed	$75–$160	$107–$229
Reduced production	$256–$426	$366–$611

[a] All costs estimates based on estimates from Thorrold (2000) and extrapolated for the proportion of land under dairying effected

[b] Taylor (2011) measured land effected in the Waikato region

[c] Ministry of the Environment (2011)

from animal waste. Nitrous oxide is produced mainly from dung, urine, and excessive nitrogen fertilizer application (Ministry of Agriculture and Forestry 2010; Pinares-Patino et al. 2009).

Dairy emissions have more than doubled from 1990 to 2012. Using energy coefficients from previous studies (Saunders and Barber 2007; Wells 2001), energy-related emissions attributed to dairy farm inputs and production (excluding animal emissions) were calculated for milksolids processed. Total energy emissions from dairy farms in 2012 were estimated between 2.1 and 2.4 million tonnes (Mt) CO_2. In 1990, emissions from enteric fermentation from dairy cattle totalled 5.03 Mt CO_2-e (23 % of the total agricultural enteric emissions), increasing to 10.77 Mt CO_2-e in 2012 (44 % of the total). Methane emissions from dairy manure were 0.46 Mt CO_2-e in 2012 (56 % of agricultural manure methane emissions) (Ministry of Agriculture and Forestry 2010). The Ministry of Agriculture and Forestry (now Ministry for Primary Industries) (2010) did not calculate fertilizer emissions by land use. However, the main nitrogen fertilizer used in New Zealand is urea and 72 % of urea was used on dairy farms in 2012 (Statistics New Zealand 2013a). Therefore, 72 % of the emissions from fertilizer use were attributed to dairy. Total animal and soil emissions from dairy farming in 2012 were estimated at 16.84 Mt CO_2-e (46 % of total agricultural emissions). Including energy emissions, total emissions are estimated to be 19.20 Mt CO_2-e, a quarter of New Zealand's total GHG emissions.

Currently, the agricultural industry in New Zealand is not required to pay for their GHG emissions but may soon be required. Under New Zealand's Emissions Trading Scheme[2] (ETS) participants with obligations acquire New Zealand Units (NZUs) to cover their emissions. One NZU covers one tonne of CO_2-e. In November 2014, NZUs were trading at NZ$4.18 (Carbon Match 2011); however, in May 2013 prices were just $0.66 per NZU. Previously, carbon prices in New Zealand were $25/t CO_2-e (Stroombergen et al. 2009); at this price, dairy emissions would cost NZ$480 million. Estimated economic costs of the impact of carbon emissions are much higher than current carbon prices. A US government study conservatively estimated the social cost of carbon (estimate of the economic damages associated with an increase in carbon emissions) at between US$12 and $128 per tonne of carbon for 2020 (NZ$15.30 to $163.80) or an average estimate of US$37 in today's dollars (NZ$47.35) (United States Government 2013). Albeit, even this is proposed to be a underestimate of the true economic costs of social harm (Revesz et al. 2014). Potential future carbon taxes may be substantially higher. A range of emission prices have been used to show potential annual costs for current dairy farming emissions (Table 2).

Clean Green Image

Initially used for tourism marketing, New Zealand's 'clean green' image has been picked up by other industries and is now fundamental to many export products. A study on the value of New Zealand's 'clean green' image found surveyed international consumers would purchase 54 % less dairy products if New Zealand's environment was perceived as degraded (Ministry for the Environment 2001). The resulting loss in revenue of dairy products from the loss of sales was estimated at between $241 and $569 million (Ministry for the Environment 2001). Other export sectors will also be affected even without directly branding themselves as a 'green' product. Furthermore, economic implications may be much higher presently, given this survey was conducted almost 15 years ago.

Summary of Environmental Costs from Dairy Impacts

The range of costs involved in mitigating or remedying impacts is estimated at between NZ$2.1 and $15 billion on a national scale (Table 3). This is equivalent to between NZ$880 and $6256 per ha of dairy land and NZ$1253 and $8910 per tonne MS. This is significantly higher than previous studies carried out in the US and UK. Moreover, if costs from biodiversity loss and ecosystem degradation were calculated, this total would be much higher. Only costs estimated on a national scale were included in the total. Although cost estimates are available for remediation at a small scale (e.g., a lake catchment), it was not possible to extrapolate for the entire country because of the large differences in cost between lakes, and is thus omitted from the total. It should be emphasized that these estimated costs

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[2] The NZ ETS was set up to encourage reductions in GHG emissions to enable reductions in total emissions below 1990 levels.

Table 2 Potential cost of dairy farming emissions with different carbon prices

Carbon price (NZ$ per tonne CO_2-e)	Cost for on-farm dairy emissions (NZ$ 2012)
$0.66—May 2013[a]	$12.67 million
$4.18—Nov 2014[b]	$80.23 million
$25.00[c]	$480 million
$47.00 (US$37)[d]	$902.4 million
$163 ($US128)[d,e]	$3.13 billion

[a] Prices dropped this low but have since been removed from Government websites

[b] Carbon Match (2011)

[c] Past world carbon price and used for past economic modeling on climate change in New Zealand (Stroombergen et al. 2009)

[d] Estimate of Social Carbon Cost (SCC) in today's dollars (NZ$47) and in 2020 (NZ$163) (United States Government 2013)

[e] Future carbon prices are expected to be costly in the 2020s, rising from NZ$50/t to $140/t (Terry 2012)

Table 3 Summary of national costs from some dairy farming impacts in New Zealand

Measure	Scale of measure	Cost (NZ$ million)	
		Lower[a]	Upper[a]
Removing nitrate from drinking water[b]	National water surpassing nitrate drinking water standards from dairy leaching annually	1784	10,705
Cost of compaction[c]	National dairy land affected by compaction	75	611
GHG emissions[d]	Potential annual cost of national dairy GHG emissions	12.7	3129
Clean green image[e]	Loss of annual value of dairy products if image was degraded	241	569
	National subtotal	2112.7	15,014

[a] The lower and upper limits are based on costs from the average estimate of impacts for which assessments were undertaken. The total is still regarded as conservative considering the valuations that were not included

[b] Costs are based on those estimated by Jensen et al. (2012) and the average nitrate leaching rate from dairying land

[c] Refer to Table 1

[d] Refer to Table 2

[e] Ministry for the Environment (2001)

are presently not real (i.e., paid directly) because much of the pollution is not cleaned up, although costly clean-up programes have been implemented in some lake catchments. Despite this, costs may become a reality in the future if further degradation requires mitigation or if New Zealander's decide they would like higher environmental standards. If environmental mitigation is deferred to the future, costs are likely to escalate and may be a huge burden to future generations.

Conclusion

There needs to be a more holistic conversation in New Zealand of whether the dairy industry is actually beneficial for the country: economically, environmentally, and socially. Although detailed cost assessments have not been carried out for management techniques aimed at reducing dairy farming impacts, from the preliminary investigation here, it is likely the cost to clean up effects will be far more than the costs of not polluting in the first place. This analysis indicates that it is likely that the environmental externalities from dairy farming may exceed the value of dairy's export revenue and the contribution to GDP (total of NZ$16.6 billion). This is not at present a cost for the dairy industry, but an estimate of the potential external cost to the public of New Zealand from dairy farming—from having a degraded environment or paying to clean up. If the dairy industry is to continue to expand and intensify, accurate reporting of the real costs needs to be used in the evaluation of the true value of this industry.

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References

Abell JM, Hamilton DP, Paterson J (2011) Reducing the external environmental costs of pastoral farming in New Zealand: experience from the Te Arawa lakes, Rotorua. Australas J Environ Manag 18:139–154. doi:10.1080/14486563.2011.591520

Addiscott TM, Benjamin N (2004) Nitrate and human health. Soil Use Manag 20:98–104. doi:10.1079/SUM2004256

Allan DJ (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu Rev Ecol Evol Syst 35:257–284

Ashley K, Cordell D, Mavinic D (2011) A brief history of phosphorus: from the philosopher's stone to nutrient recovery and reuse. Chemosphere 84:737–746

Awatere S (2005) Can non-market valuation measure indigenous knowledge? In: Australian Agricultural and Resource Economics Society, Australia, p 15

Ball A (2006) Estimation of the burden of water-borne disease in New Zealand: preliminary report. Ministry of Health, Wellington

Ballantine DJ, Davies-Colley RJ (2009) Water quality trends at NRWQN sites for the period 1989–2007. National Institute of Water & Atmospheric Research, Hamilton

Bertram G (2013) Green border control: issues at the environment/economy border. Simon Terry Associates Research, Wellington

Beukes PC, Scarsbrook MR, Gregorini P, Romera AJ, Clark DA, Catto W (2012) The relationship between milk production and farm-gate nitrogen surplus for the Waikato region, New Zealand. J Environ Manag 93:44–51. doi:10.1016/j.jenvman.2011.03.013

Carbon Match (2011) Carbon Match. Low-cost trading. Direct contracts. Transparent prices. Open every weekday between 3 pm and 4 pm (NZ time). Carbon Match. http://www.carbonmatch.co.nz/. Accessed 11 Nov 2014

Cassells SM, Meister AD (2000) Cost of land-based effluent disposal to the New Zealand dairy sector. Department of Applied and International Economics, Massey University, Palmerston North

Collins R et al (2007) Best management practices to mitigate faecal contamination by livestock of New Zealand waters. N Z J Agric Res 50:267–278

Cordell D, Drangert J-O, White S (2009) The story of phosphorus: global food security and food for thought. Glob Environ Change 19:292–305. doi:10.1016/j.gloenvcha.2008.10.009

Costanza R et al (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Cullen R, Hughey K, Kerr G (2006) New Zealand freshwater management and agricultural impacts. Aust J Agric Resour Econ 50:327–346. doi:10.1111/j.1467-8489.2006.00338.x

Daily GC et al (1997) Ecosystem services: benefits supplied to human societies by natural ecosystems Issues. Ecology 2:1–16

LIC, DairyNZ (2012) New Zealand dairy statistics 2011–12. Livestock Improvement Corporation, DairyNZ, Hamilton

DairyNZ (2013) DairyNZ Economic Survey 2011–12. DairyNZ, Hamilton

Daly H (2005) Economics in a full world. Sci Am 293:100–107

Davies-Colley R (2000) "Trigger" values for New Zealand rivers. National Institute of Water & Atmospheric Research, Hamilton

Davies-Colley R, Nagels JW (2002) Effects of dairying on water quality of lowland stream in Westland and Waikato. Proc N Z Grassl Assoc 64:107–114

Davies-Colley R, Cameron K, Francis G, Bidwell V, Ball A, Pang L (2003) Effects of rural land use of water quality. National Institute of Water & Atmospheric Research, Hamilton

Davies-Colley R, Nagels JW, Smith RA, Young RG, Phillips CJ (2004) Water quality impact on a dairy cow herd crossing a stream. N Z J Mar Freshwat Res 38:569–576

de Klein CAM, Ledgard S (2001) An analysis of environmental and economic implications of nil and restricted grazing systems designed to reduce nitrate leaching from New Zealand dairy farms. I. Nitrogen losses. N Z J Agric Res 44:201–215. doi:10.1080/00288233.2001.9513478

Dewes A (2012) Statement of evidence of Dr Alison Dewes on behalf Wellington Fish and Game Council in the matter of appeals under clause 14 of the First Schedule to the Resource Management Act 1991 concerning the proposed One Plan for the Manawatu-Wanganui Region. Horizons Regional Council

Donnison AM, Ross CM (1999) Animal and human faecal pollution in New Zealand rivers. NZ J Mar Freshwat Res 33:119–128

Drewry JJ (2006) Natural recovery of soil physical properties from treading damage of pastoral soils in New Zealand and Australia: a review. Agric Ecosyst Environ 114:159–169

Duda M, Shaw JS (1997) Life cycle assessment. Soc Sci Public Policy 35:38–43

Ekins P, Folke C, De Groot R (2003) Identifying critical natural capital. Ecol Econ 44:159–163

Elliott AH, Alexander RB, Schwarz GE, Shankar U, Sukias JPS, McBride GB (2005) Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. J Hydrol 44:1–27

Environment Bay of Plenty, Rotorua District Council, Te Arawa Lakes Trust (2006) Lake Okaro action plan. Environment Bay of Plenty, Rotorua District Council & Te Arawa Maori Trust Board

Environment Canterbury (2013a) Annual groundwater quality survey 2011. Environment Canterbury Regional Council

Environment Canterbury (2013b) Annual groundwater quality survey 2012. Environment Canterbury Regional Council

Environment Waikato (2008) The condition of rural water and soil in the Waikato region: risks and opportunities. Environment Waikato, Hamilton

Ford R, Taylor K (2006) Managing nitrate leaching to groundwater: an emerging issue for Canterbury. Water Rights Trust

Ford-Robertson J (2013) TDR symposium. Ford-Robertson Initiatives, Rotorua

Hackett SC (1998) Environmental and natural resources economics: Theory, policy, and the sustainable society. Sharpe, University of Michigan, M.E

Hamill K, MacGibbon R, Turner J (2010) Wetland feasibility for nutrient reduction to Lake Rotorua. Opus, Whakatane

Index Mundi (2012) Palm kernel meal production by country in 1000 MT. http://www.indexmundi.com/agriculture/?commodity=palm-kernel-meal&graph=production. Accessed 12 March 2013

Jensen VB, Darby J, Seidel C, Gorman C (2012) Drinking water treatment for nitrate. Technical Report 6 in Addressing nitrate in California's drinking water with a focus on Tulare Lake Basin and Salinas Valley Groundwater. Centre for Watershed Sciences, University of California, Davis

Larned ST, Scarsbrook MR, Snelder TH, Norton NJ, Biggs BJF (2004) Water quality in low elevation streams and rivers of New Zealand: recent state and trends in contrasting land cover classes. N Z J Mar Freshwat Res 38:347–366. doi:10.1080/00288330.2004.9517243

Larned S, Scarsbrook M, Snelder T, Norton N (2005) Nationwide and regional state and trends in river water quality 1996-2002. National Institute of Water & Atmospheric Research, Christchurch

Ledgard SF, Thom ER, Singleton PL, Thorrold BS, Edmeades DC (1996) Environmental impacts of dairy systems. In: Proceedings of Ruakura farmers' conference, AgResearch, Hamilton, New Zealand

Ledgard S, Steel K, Roberts AHC, Journeaux PR (2000) Use of OVERSEER^{TM} to compare farm systems and countries for nutrient balances, losses and efficiency. In: Currie LD, Loganathan P (eds) Soil research—a knowledge industry for land-based exporters. Occasional Report No. 14. Fertilizer and Lime Research Centre, Palmerston North, New Zealand, pp 83–91

Ledgard S, Schils R, Eriksen J, Luo J (2009) Environmental impacts of grazed clover/grass pastures. Ir J Agric Food Res 48:209–226

Ledgard S, Judge A, Smeaton DC, Boyes M (2010) Greenhouse gas emissions from Rotorua dairy farms: summary report. AgResearch, Hamilton

Lilburne L, Webb T, Ford R, Bidwell V (2010) Estimating nitrate-nitrogen leaching rates under rural land uses in Canterbury. Environment Canterbury Regional Council, Christchurch

Mackay AD (2008) Impacts of intensification of pastoral agriculture on soils: current and emerging challenges and implications for future land uses. N Z Vet J 56:281–288

MacLeod CJ, Moller H (2006) Intensification and diversification of New Zealand agriculture since: an evaluation of current indicators of land use change. Agric Ecosyst Environ 115:201–218. doi:10.1016/j.agee.2006.01.003

Marsh D (2012) Water resource management in New Zealand: jobs or algal blooms? J Environ Manag 109:33–42

Menneer JC, Ledgard S, McLay C, Silvester W (2001) What impact does dairy cow pugging have on clover N_2 fixation and long-term farm production? Proc N Z Grassl Assoc 63:63–67

Ministry for the Environment (2001) Our clean green image: what's it worth?. Ministry for the Environment, Wellington

Ministry for the Environment (2007a) Environment New Zealand 2007. Ministry for the Environment, Wellington

Ministry for the Environment (2007b) Groundwater quality in New Zealand: state and trends 1995–2006. Ministry for the Environment, Wellington

Ministry for the Environment (2009) Water quality in selected dairy farming catchments: a baseline to support future water-quality trend assessments. Ministry for the Environment, Wellington

Ministry for the Environment (2010) Land: soil health environmental snapshot. Ministry for the Environment, Wellington

Ministry for the Environment (2011) Soil health. Ministry for the Environment. http://www.mfe.govt.nz/environmental-reporting/land/soil-health/. Accessed 16 April 2013

Ministry of Agriculture and Forestry (2010) Agricultural sector projected emissions. Ministry for the Environment, New Zealand

Ministry of Health (2008) Drinking-water standards for New Zealand 2005 (Revised 2008). Ministry of Health, Wellington

Moller H et al (2008) Intensification of New Zealand agriculture: implications for biodiversity. N Z J Agric Res 51:253–263

Nguyen ML, Sheath GW, Smith CM, Cooper AB (1998) Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. N Z J Agric Res 41:279–290. doi:10.1080/00288233.1998.9513312

NIWA (2010a) Appendix 32: non-market values. In: NIWA (ed) Waikato River independent scoping study. NIWA, Hamilton

NIWA (2010b) Waikato River independent scoping study. National Institute of Water & Atmospheric Research, Hamilton

Pande TN (2002) Pasture dynamics under cattle treading. Massey University, PhD

Parliamentary Commissioner for the Environment (2004) Growing for good: intensive farming, sustainability and New Zealand's environment. Parliamentary Commissioner for the Environment, Wellington

Perman R, Ma Y, McGivray J (1996) Natural resource and environmental economics. Longman Publishing Group, London

Pimentel D (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environ Dev Sustain 7:229–252

Pinares-Patino CS, Waghorn GC, Hegarty RS, Hoskin SO (2009) Effects of intensification of pastoral farming on greenhouse gas emissions in New Zealand. N Z Vet J 57:252–261. doi:10.1080/00480169.2009.58618

Powell JM, Gourley CJP, Rotz CA, Weaver DM (2010) Nitrogen use efficiency: a potential performance indicator and policy tool for dairy farms. Environ Sci Policy 13:217–228

Pretty JN et al (2000) An assessment of the total external costs of UK agriculture. Agric Syst 65:113–136

Prugh T, Costanza R, Daly H, Goodland R, Cumberland JH, Norgaard RB (1999) Natural capital and human economic survival. CRC Press-Lewis Publishers, Boca Raon, FL

Rajanayaka C, Donaggio J, McEwan H (2010) Update of water allocation data and estimate of actual water use of consented takes-2009–10. Aqualinc, New Zealand

Revesz RL et al (2014) Global warming: improve economic models of climate change. Nature 508:173–175

Roberts A, Morton J (2009) Fertiliser use on New Zealand dairy farms: the principles and practice of soil fertility and fertiliser use on New Zealand dairy farms. Fert Research, Auckland

Rockström J et al (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14(2):32 (online). http://www.ecologyandsociety.org/vol14/iss2/art32/

Rodda HJE, Wilcock RJ, Shankar U, Thorrold B (1999) The effects of intensive dairy farming on stream water quality in New Zealand. In: Heathwaite L (ed) Proceedings of international union of geodesy and geophysics symposium, Birmingham, United Kingdom, July, 1999. International Association of Hydrological Sciences

Rosemarin A, de Bruijne G, Caldwell I (2009) The next inconvenient truth peak phosphorus. Broker 15:6–9

Russell JR, Betteridge K, Costall DA, Mackay AD (2001) Cattle treading effects on sediment loss and water infiltration. J Range Manag 54:184–190

Saunders C, Barber A (2007) Comparative energy and greenhouse gas emissions of New Zealand's and the UK's dairy industry. Lincoln University, Christchurch

Schilling C, Zuccollo J, Nixon C (2010) Dairy's role in sustaining New Zealand—the sector's contribution to the economy. New Zealand Institute of Economic Research, Wellington

Smith CM, Wilcock RJ, Vant WN, Smith DG, Cooper AB (1993) Towards sustainable agriculture: freshwater quality in New Zealand and the influence of agriculture. National Institute of Water & Atmospheric Research, Hamilton

Sparling G, Schipper L (2004) Soil quality monitoring in New Zealand: trends and issues arising from a broad-scale survey. Agric Ecosyst Environ 104:545–552

Statistics New Zealand (1998) Agriculture statistics (1996)—reference reports. Statistics New Zealand. http://www.stats.govt.nz/browse_for_stats/industry_sectors/agriculture-horticulture-forestry/agriculture-stats-1996.aspx. Accessed 8 Aug 2012

Statistics New Zealand (2006) Fertiliser use and the environment. Statistics New Zealand. http://www3.stats.govt.nz/environment/Fertiliser_use_and_the_environment_Aug06.pdf

Statistics New Zealand (2012) Infoshare. Statistics New Zealand. http://www.stats.govt.nz/infoshare/

Statistics New Zealand (2013a) 2012 Agricultural census tables. Statistics New Zealand. http://www.stats.govt.nz/browse_for_stats/industry_sectors/agriculture-horticulture-forestry/2012-agricultural-census-tables.aspx

Statistics New Zealand (2013b) Harmonised Trade—Imports. Statistics New Zealand. http://www.stats.govt.nz/infoshare/TradeVariables.aspx?DataType=TIM

Stroombergen A, Schilling C, Ballingall J (2009) Economic modelling of New Zealand climate change policy. Report to Ministry for the Environment. NZIER and Infometrics, New Zealand. https://www.climatechange.govt.nz/emissions-trading-scheme/building/reports/economic-modelling/economic-modelling-of-new-zealand-climate-change-policy.pdf

Tait P, Cullen R (2006) Some external costs of dairy farming in Canterbury. In: 50th Australian Agricultural and Resource Economics Society annual conference, Sydney, Australia

Taylor M (2011) Soil quality and trace element monitoring in the Waikato Region 2009. Waikato Regional Council, Hamilton

Tegtmeier EM, Duffy MD (2004) External costs of agricultural production in the United States. Int J Agric Sustain 2:1–20

Templet PH (1995) Grazing the commons: an empirical analysis of externalities, subsidies and sustainability. Ecol Econ 12:141–159

Terry S (2012) The carbon budget deficit. Sustainability Council, Wellington

Thorrold B (2000) Environmental impacts of wintering systems. Paper presented at the South Island Dairy Event conference

Tilman D (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc Natl Acad Sci USA 96:5995–6000. doi:10.1073/pnas.96.11.5995

Townsend CR, Arbuckle CJ, Crowl TA, Scarsbrook MR (1997) The relationship between land use and physicochemistry, food resources and macroinvertebrate communities in tributaries of the Taieri River, New Zealand: a hierarchically scaled approach. Freshw Biol 37:177–191

Turner RK, Pearce D, Bateman I (1994) Environmental economics: an elementary introduction. Harvester Wheatsheaf, New York, London

United States Government (2013) Technical update of the Social Cost of Carbon for Regulatory Impact Analysis—Under Executive Order 12866. United States Government

Verburg P, Hamill KD, Unwin M, Abell J (2010) Lake water quality in New Zealand 2010: status and trends. National Institute of Water & Atmospheric Research, Hamilton

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499

Wells C (2001) Total energy indicators of agricultural sustainability: dairy farming case study. Ministry of Agriculture and Forestry, Wellington

Wilcock RJ, Nagels JW, Rodda HJE, O'Connor MB, Thorrold BS, Barnett JW (1999) Water quality of a lowland stream in a New Zealand dairy farming catchment. N Z J Mar Freshwat Res 33:683–696

Wilcock RJ, Monaghan R, Thorrold B, Meredith AS, Betteridge K, Duncan MJ (2007) Land-water interactions in five contrasting dairying catchments: issues and solutions. Land Use Water Resour Res 7:2.1–2.10

Willis R (2001) Farming. Asia Pac Viewp 42:55–65

World Resources Institute (2013) CAIT 2.0 WRI's climate data explorer. World Resources Institute. http://www.wri.org/tools/cait/. Accessed 2013