The Water-Use Efficiency of Dairy Farming in Eastern Ontario: A Case Study

by

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ABSTRACT

An excel-based calculator (WatBal-Dairy) was created as a framework for water-use accounting of dairy farm operations. The water-use of alfalfa was measured *in situ* and compared to Denitrification and Decomposition (DNDC) model estimates. Results highlighted the need to calibrate DNDC to Canadian growing conditions with the model over-estimating measured evapotranspiration (ET) (34.1%), net ecosystem exchange of carbon dioxide (11.8%) and biomass (9.7%), while under-estimating soil moisture (-12%). The WatBal-Dairy prototype was created using validated empirical models for cattle and barn water-use and tested using operational data including measured cattle intake and washwater from a working dairy farm near Ottawa. The farm water footprint was 1025.7 kg H_2O kg^{-1} FPCM; precipitation (green water) accounted for 99.35% of the footprint and pumped (blue) water 0.45%. The field environment (crops and pasture) was responsible for 99.6% of farm water consumption, i.e. water made unavailable for other uses.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Definition
AAFC	Agriculture and Agri-Food Canada
AWDM	Agriculture Water Demand Model
Can-DNDC	Canadian Denitrification-Decomposition Model
CENTURY	Century soil organic Model
CO_2	Carbon Dioxide
DayCent	Daily CENTURY Model
DM	Dry Matter
DMI	Dry Matter Intake
DNDC	Denitrification-Decomposition Model
EGLHLE	Eastern Great Lakes Hudson Lowlands Ecosystem
EPIC	Environmental Policy Integrated Climate Model
ET	Evapotranspiration
FCM	Fat Corrected Milk
FPCM	Fat and Protein Corrected Milk
FW	Fecal Water
FWI	Free Water Intake
H_2O	Water
H_2O-e	Water Equivalent
ISO	International Standards Organization
LCA	Life Cycle Assessment
LE	Latent Heat Energy
MC	Moisture Content
M_E	Manure Excretions
NEE	Net Ecosystem Exchange
NMAN	Nutrient Management Software Program (OMAFRA)
NOP	National Organic Program (USDA)
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
RCW	Respiratory Cutaneous Water
RWI	Ration Water Intake
SCLCI	Swiss Center for Life Cycle Inventories
SOCRATES	Soil Organic Carbon Reserves and Transformations in Agro-Ecosystems Model
SWAT	Soil and Water Assessment Tool
TIPI-CAL	Technology Impact Policy Impact Calculator
TWI	Total Water Intake
U_e	Urinary Excretions
UW	Water in Urine
WFN	Water Footprint Network
WFP	Water Footprint
WFP_{WFN}	Water Footprint (Water Footprint Network)
WFP_{LCA}	Water Footprint (Life Cycle Assessment)
WUE	Water-Use Efficiency

1. Introduction

With a rising population, economic growth, pollution and climate change stressing existing freshwater resources in Canada (NRCan 2005; NRTEE 2010; CCA 2013; Schreier and Wood 2013), water experts from across the country have put forth recommendations to protect this resource. Recommendations include the development of common quantification techniques for primary users, common requirements for water licences and reporting, and the pricing of water-use (NRTEE 2012). Access to freshwater is critical to dairy production with feed crops, animal intake, and cleaning all requiring significant inputs (Brown et al 2009). With the anticipated freshwater scarcity, dairy producers will be faced with greater competition for the resource from both domestic and industrial users (NRTEE 2010; CCA 2013; Schreier and Wood 2013); competition that in other countries has frequently led to a decline in agricultural water allocation (FAO 2012). Additionally, with the anticipated implementation of water pricing and licencing fees, dairy farmers will be faced with increasing production costs. Since 1970, Canadian dairy farms have decreased in number by over 90% (AAFC/DFC/DPAC/CDC 2014); yet, through advancements in genetics, nutrition and increases in herd size and acreage, production has continued to meet market demands (StatsCan 2014). With the trend towards larger herds and acreages expected to continue, augmented single farm licencing and water use fees may potentially threaten the economic viability of Canadian dairy production.

To address the potential impact of water scarcity, Canadian dairy producers are proactively committing to improve the efficiency of water-use at the farm level through the identification and implementation of sustainable water management practices that protect the resource and ensure production of a quality product (CDF 2014). This commitment requires access to dependable measurements of water-use and validated water-balance models for each part of the dairy farm system (NRTEE 2010; CCA 2013). At present, there is limited and inconsistent water-use data available with no standardized methodology for collection and reporting (Corkal and Diaz 2011; CCA 2013); a situation attributed to the complexity of water governance in this country (Boyd 2003; NRCan 2005; Corkal and Diaz 2011). Without knowledge of current water-use in field crop, pasture, cattle and barn processes, it is not possible to objectively assess water-use in farm operations, identify areas of concern (hotspots with excessive water-use or loss, for example, over-irrigation, washwater waste or pipe leakage), or make informed decisions relating to best management practices. This situation, however, can be corrected through the development of an integrated water-use framework that quantifies the water dynamics of typical dairy farm processes in a uniform, structured, and transparent manner.

For the purpose of this study, water is partitioned according to Hoekstra et al. (2011) as: water from precipitation (green water) that is lost through evaporation, transpiration or incorporated into the product (crop); surface and ground water (blue water) that becomes unavailable for future use within the originating catchment (e.g. irrigated water); and, polluted outputs (grey water). 'Water-use' is defined as the producer's "on farm" field to farm-gate water use and includes green and blue water used directly in farm operations in the field, pasture, cattle and barn environments. Water-use in this study does not include water used along the supply chain such as water used in the production of chemical fertilizers and pesticides, farm equipment or feed grown off-site that is used on the farm.

Further, to facilitate comparison in this study, farm water-use is assessed during two distinct temporal periods. The "thermoneutral period" refers to the period from September 25 to October 4, 2014, when temperatures fell within the thermoneutral (comfort) zone for dairy cattle. The thermoneutral zone is the range of environmental temperature (5 ºC to 25 ºC) in which cattle maintain body temperature without any additional expenditure of energy (McDowell 1972). The cool period refers to the period from February 13 to 22, 2015, when temperatures remained consistently below the thermoneutral zone. Note that due to time restraints associated with the study, no data was collected relevant to "hot" temperature conditions, i.e. temperatures above the thermoneutral zone.

1.1. Water-Use Framework Considerations

A framework provides a structure and direction on a preferred way to do something but is flexible enough to adapt to variable conditions and needs (Ellis 2010). This paper focuses on the development and testing of a structured, yet flexible, prototype framework to quantify on a dairy farm. The framework is presented as an Excel calculator named “WatBal-Dairy” that is based on the hydrological cycle and water balance: scientific concepts which may be adapted to varying temporal and spatial scales (Winter et al. 1998).

By designing the framework based on the water balance of the individual farm environments (crops, pasture, cattle and barn), as well as the complete farm-system, the calculator provides flexibility. First, the identified parameters, factors that uniquely identify the inputs, outputs and storage in each farm environment, accommodate the diversity of environmental and management systems that impact dairy farm water-use. In the Canadian context, this entails the ability to account for: (a) the distribution of almost 12,000 dairy farms of various sizes throughout the provinces (CDIC 2014); (b) variations in crop management systems (CCA 2013); (c) on-going changes from pasture grazing to confinement-based management systems (McCartney 2011); (d) variable in-barn milking and cooling systems (Canwest,Valacta 2013) and; (e) differences in feed composition between farms and regions (Sheppard et al. 2011; Quantis, AGECO and CIRAIG 2012). Second, the calculator provides the flexibility to conduct either integrated or non-integrated accounting of on-farm water-use. 'Integrated' refers to the connectivity in water flow between the field, cattle and the barn, (i.e. the linked nature of water in manure input to fields, crop intake, cattle feed intake and cattle output). Integrated accounting provides a farm-level assessment of water-use while still enabling focused assessment of water-use within individual environments (crops, forages, animals, barns). Third, by individually parameterizing water flows and storage in each environment, it is expected that a degree of "responsiveness" will be incorporated into the framework. Through the use of modeling and empirical equations reflecting environmental and temporal variables, the impact of management changes on water-use efficiency are evident. For example, rather than assigning a constant volume of water intake based on the life stage of cattle, the calculator reflects changes in water intake in response to dietary composition. Finally, while the primary purpose of the framework is to provide a quantitative tool to improve the efficiency of water-use on Canadian dairy farms, the computed data may also be used to populate fields in water footprinting methodologies. A water footprint (WFP) is an accounting of freshwater-use related to the production of goods and services at varying scales .i.e. individual, business, community or country level (Hoekstra et al. 2011). Common methodologies include the WFP of the Water Footprint Network (WFN) (Hoekstra et al. 2011) and the International Standards Organization's (ISO) water inventory (ISO 2014).

Development of this calculator required: 1) a review of existing scientific literature to find relevant water-use equations, factors, and models; 2) *in situ* measurements to validate the models and equations, and; 3) consultation with dairy producers to accurately characterize farm management practices and test WatBal-Dairy.

1.2. Water-Use Quantification Considerations

The quantification of water-use in the field, pasture, cattle and barn environments through *in situ* measurements is considered ideal; however, obtaining measurements from individual farms on a wide-scale basis is not feasible. Modeling provides a less expensive and less time consuming alternative to *in situ* measurements and can be applied over various spatial and temporal scales (Winters et al. 1998; CCA 2013; Grant et al. 2014). The accuracy of models, however, depends on calibration and validation with reliable data to ensure relevancy to the subject matter (Grant et al. 2014). Calibration reduces simulation uncertainty by inferring values for input parameters through comparison of output data to observed data (Zhang et. al. 2002), whereas validation assesses the accuracy of a model through comparison of output data to data not used in the calibration (Arnold et al. 2012).

The Denitrification and Decomposition (DNDC) model (Li et al. 1992a/b, 1994; Li 2000) is a process-based biogeochemical crop model that simulates agricultural carbon, nitrogen and water cycles (Zhang et al. 2002). Agriculture and Agri-Food Canada (AAFC) have developed a sub-model within DNDC (Can-DNDC) to simulate cropping systems in western and eastern Canada (Kröbel et al. 2011). To date, algorithms have been calibrated and validated within the sub-model to reflect Canadian growing conditions for several dairy feed crops including corn, soybean, and spring wheat (Kröbel et al. 2011; Smith et al. 2012; Smith et al. 2013; Grant et al. 2014). As such, DNDC is being considered as a potential tool for population of crop water-use parameters in WatBal-Dairy.

The use of DNDC, however, remains limited as growth algorithms for perennial feed crops including alfalfa (hay) have not yet been calibrated or validated in a Canadian context. This is of concern in relation to the accuracy of WatBal-Dairy calculations as alfalfa is Canada's most widely grown forage legume, and the premium forage for dairy cattle (AAFC 2013). To assist with the correction of this situation, *in situ* alfalfa growth curve and water-use measurements have been conducted in this study to facilitate testing of the existing alfalfa algorithms, identify shortcomings and provide benchmarks that will support development of a Canadian-based alfalfa model.

1.3. Research Objectives

This study addresses the question of how to correct the void in dependable measurements of water-use and validated water-balance models that currently prevents assessment of water-use efficiency in Canadian dairy production. The primary goal of this study is to create and test a prototype water-use efficiency framework that will: (a) bring uniformity, structure and direction to the quantification of water-use in the dairy sector and; (b) provide reliable estimates of field to farm-gate water-use to enable informed decisions about improved management practices.

The theoretical and practical development of the framework addresses questions relevant to the identification of the specific water flows requiring quantification at the farm level, and the identification of models which will afford consistency, yet provide the flexibility needed to reflect the diversity of Canadian dairy farming. The testing of the practical framework with an actual farm case study provides an indication of the potential broad-scale use of the calculator with answers to questions such as, "What is the major water-use in the case-study dairy farm?" and "How might the water-use on this farm be better managed?"

The study is unique as it provides *in situ* field measurements for validation and calibration of the DNDC alfalfa growth algorithm, provides *in situ* measurements for validation of cattle and barn water-use equations, and introduces an Excel-based calculator for integrated quantification of blue and green water dynamics in the field, pasture, cattle and barn environments.

Specific objectives of the study were to:

1) conduct *in situ* measurements of water flows and storage from alfalfa study sites to identify shortcomings in the existing DNDC algorithm relating to growth, evapotranspiration (ET), net ecosystem exchange (NEE) and soil moisture, and provide datasets for future calibration and validation of alfalfa algorithms in Can-DNDC;

2) compare water-use equations for animals and barn-cleaning to *in situ* measurements in a typical tie-stall barn management system, and;
3) create WatBal-Dairy, an Excel field to farm-gate water-use calculator designed to quantify water flows and storage in dairy production, and test the calculator with an actual farm case-study.

2. Literature Review

2.1. Existing Water Footprint Methodologies and Quantification Data

2.1.1. International Status

In recent years, the WFP has been the primary tool used to quantify water-use in dairy production; however, the application of the methodology and the quantification of results have been inconsistent and preclude comparison. This is largely attributable to disagreement among researchers as to the purpose of the 'WFP'. The WFP concept, as introduced by Hoekstra in 2002 (WFP_{WFN}), is a comprehensive accounting of water-use that includes measurement of direct and indirect green and blue water consumption and grey polluted outputs (Hoekstra et al. 2011). In the past 7 years, opposition to the WFP_{WFN} has arisen among researchers who believe it is of limited value unless coupled with an assessment of social and environmental impacts within a life cycle assessment (LCA) (Berger and Finkbeiner 2010; Ridoutt and Pfister 2010). Supporters of the LCA WFP (WFP_{LCA}) claim that while quantitative indicators are required to determine water inventory, the main focus of the WFP should be the assessment of environmental impacts (Boulay et al. 2013). The conflict over the purpose of the WFP has shifted the focus of scientific research from quantification for the purposes of improving water-use efficiency to development of LCA methods (Table 1).

With the focus on methodology development, there has been no standardization of quantification boundaries, scope, or parameters in dairy production studies. This has resulted in significant variation in WPF_{WFN} and WPF_{LCA} quantification results and points to the need for a consistent framework to enable effective comparison of water-use in dairy production (Table 2). Furthermore, with the focus on methodology development, there has been little emphasis placed on the identification of hotspots and mitigation strategies: the primary interest of dairy farmers. Only two of the studies noted in Table 2 (Hortenhuber et al. 2012; Zonderland-Thomassen and Ledgard 2012) provided suggestions as to how water use might be improved at the producer level.

Table 1 Summary of recent water footprint methodologies including the quantitative water footprint (WFP) of the Water Footprint Network (WFN) and various life cycle assessments (LCA) footprints.

STUDY/GUIDELINE	SOURCE	WATER FLOW CONSIDERATIONS
Water Footprint / Water Footprint Network	Hoekstra et al. 2011	• Direct and indirect consumption from green and blue sources • Grey water calculated through dilution principles* • no consideration given to non-polluted blue return flows
River Basin Water Footprint (LCA)	Mila i Canals et al. 2009	• Evaporated surface, ground and fossil water • incorporates land use changes into calculations to assess impact on rainwater availability and loss
Mid-Point/End Point Water Footprint (LCA)	Pfister et al. 2009	• Consumptive and degradative surface and ground water-use • Introduction of Water Stress Index to assess consumption impacts in relation to scarcity
Eco-Scarcity Water Footprint (LCA)	Frischknecht et al. 2009	• total input of water abstracted for consumption or production
Stress-Weighted Water Footprint (LCA)	Ridoutt and Pfister 2010	• Blue and grey water as per Hoekstra • Land use impact used for rain volumes. • Net consumptive water-use multiplied by regional Water Stress Index to determine stress-weighted WFP. • Introduces H_2O equivalency (H_2O-e)
Qualified Water Footprint (LCA)	Peters et al. 2010	• Inputs classified by source: flows (precipitation, surface water) and funds (ground water). • Outputs classified by quality: high, moderate, low and alienated
Categorized (LCA)	Boulay et al. 2011	• Considers quantity and quality of both inputs and outputs • Water inventory based on flows of precipitation, surface and ground water
Equivalency Water Footprint (LCA)	Ridoutt and Pfister 2013	• Single score WFP calculated by adding green and blue consumptive water, and degradative water-use using H_2O equivalency (Ridoutt and Pfister 2012)

*Dilution – volume of water required to dilute a load of pollutants to a state reflecting ambient water standards and conditions

Table 2 Result summary of Water Footprint Network and Life Cycle Assessment stress-weighted (H_2O equivalent) water footprint studies for water-use in dairy production with boundaries, scope, parameters and primary data sources.

Study	Water Footprint Results	Boundaries/Scope and Parameters	Primary Data Sources
Mekonnen and Hoekstra (2010) Water Footprint Network	Global average (7 countries) 1020 m^3 ton^{-1}	• Field to consumer / direct + indirect green, blue and grey flows for grazing, mixed and industrial systems to get weighted avg. • Feed, drinking, servicing, feed mixing (animal lifetime avg.)	• Crop model for crop water-use • Existing studies to estimate most values
Sultana et al. (2010) Water Footprint Network	12 farms (6 Countries) 430L kg^{-1} in US to 2400L kg^{-1} in Pakistan	• Field to farm-gate / blue flows • Feed production, drinking, servicing, feed intake	• Used Technology Impact Policy Impact Calculations Model (TIPI-CAL) to collect data and calculate variables
Hortenhuber et al. (2012) Water Footprint Network modified	One farm - Austria 940L kg^{-1}	• Farm and upstream supply chain / direct + indirect green, blue and grey flows (included green volume of deforestation) • Precipitation, irrigation, drinking, cleaning, cooling, production of fertilizers and pesticides, processing, packaging, transport	• Not mentioned in report
Zonderland-Thomassen et al. (2012) Water Footprint Network	Two farms - Australia FARM 1 945L kg^{-1} FPCM FARM 2 1084L kg^{-1} FPCM (Fat and protein corrected milk)	• Field to farm-gate/ direct + indirect green, blue and grey flows • Animals sold for meat, feed production, imported feed, fertilizer, electricity, pasture, drinking water, respiratory loss, cleaning, effluent, and water in milk	• Existing studies • OVERSEER sub-model for silage production, ET, crop incorporation, irrigation ET and nitrate leaching
Zonderland-Thomassen et al. (2012) Life Cycle Stress-Weighted for Consumption and Abstration	Two farms – Australia WFP consumption (FPCM) FARM 1 0.011 L H_2O-e kg^{-1} FARM 2 7.1 L H_2O-e kg^{-1} WFP abstraction (FPCM) FARM 1 0.165 L H_2O-e kg^{-1} FARM 2 11.1 L H_2O-e kg^{-1}	• Field to farm-gate / blue water consumed and abstracted at field and farm level including direct and indirect flows • Comprehensive parameterization as noted for WFN WFP above	• As above
De Boer et al. (2013) Life Cycle Inventory/ Stress-Weighted	Dutch WFP – single model Inventory 66L kg^{-1} FPCM 33 L H2O-e kg^{-1} FPCM	• Field to farm-gate / direct and indirect consumptive blue flows • Irrigation, infiltration, runoff, processing of fertilizer and fossil energy, drinking and cleaning	• Existing studies including International Food Policy Research Institute grid data, AQUASAT, Ecoinvent
Hortenhuber et al. (2014) Water Footprint Network Modified / Life Cycle Assessment - Stress-Weighted	Austrian WFP – two farms FARM 1 683L kg^{-1} FARM 2 699L kg^{-1} Local Weighted Grey + Blue FARM 1 ~310 H_2O-e kg^{-1} FARM 2 ~570 H_2O-e kg^{-1}	• Field to farm-gate / direct and indirect green, blue and grey flows (included green volume for deforestation of tropical forest) plus impact weighted water footprint for grey and blue • Irrigation, drinking, cleaning, cooling, production of fertilizers and pesticides, processing, packaging, transport	• Assumed blue evapotranspiration to be 1% for grain, 2% for corn based on existing literature • EPIC Model for evapotranspiration • Used data from existing studies for drinking and cleaning water
Huang et al. (2014) Life Cycle Assessment - Inventory / Stress-Weighted	Northeast China – four farms Inventory Average 69L kg^{-1} Local 11 L H_2O-e kg^{-1} California 461 L H_2O-e kg^{-1} New Zealand 0.01L H_2O-e kg^{-1}	• Field to farm-gate / blue consumptive water for local and imported products from California and New Zealand • Irrigation, production of fuels, fertilizers, etc., feed, drinking, servicing, electricity, coal, milk, factory electricity, coal, diesel, packaging	• First hand survey data, farmers, experts, Chinese Life Cycle database, US Life Cycle database, Ecoinvent, data from processing plant and existing studies

In 2014, the ISO released guidelines designed to bring resolution to the WFP debate. The standard introduced in ISO 14046:2014 is based on a life cycle approach and clearly addresses the need for an impact assessment. The calculation of the life cycle inventory (LCI) is a required step in the LCA process and includes elementary flows defined as, “water entering the system that is being studied that has been drawn from the environment, or water leaving the system being studied that is being released into the environment”. The user is responsible for the identification of elementary flows and measurement parameters in accordance with study objectives but, subject to a sensitivity analysis, may omit life cycle stages, inputs or outputs providing they do not significantly change the conclusions (ISO 2014). While the ISO guidelines provide direction for conducting a LCA, it is likely that future studies will show that they do not resolve the problem of inconsistency in identifying water-use parameters nor do they remove subjectivity from water-use quantification.

A water balance framework will help to resolve the matter of inconsistency and subjectivity for both the WFP_{WFN} and WFP_{LCA} relative to on-farm dairy production water-use. The framework parameters will offer standardized quantification of green, blue and grey water parameters that may be used in WFP_{WFN} studies or other quantitative methodologies that will satisfy the needs of the LCI and facilitate impact assessments for issues such as freshwater eutrophication, acidification or ecotoxicity. Additionally, framework calculator results will be more responsive than the generic data typically used in WFP studies. This capability will provide farmers with the ability to evaluate the impact of their actions on water-use efficiency.

2.1.2. Canada

Data relating to dairy production water-use in Canada were, for the most part, limited in availability. Much of the literature relied on government data, and generally provided no indication of how the figures were calculated. Results were often amalgamated with data from other agricultural sectors or lacked sufficient detail to enable comparison. For example, Statistics Canada provided detailed irrigation values by province and drainage region for field crops in *Agricultural Water Use in Canada 2012* (StatsCan 2013); but failed to designate water-use by agricultural sector. And, in another report, Statistics Canada (2010) estimated the total environmental water supply required for dairy irrigation, cattle intake, cleaning of housing and milking equipment; but provided no breakdown of water-use by activity.

Reported data also frequently failed to reflect the variation in water-use associated to differences in crop, milking and manure management systems, feed composition and environmental conditions (NRTEE 2010; Zonderland-Thomassen and Ledgard 2012) which are prevalent between ecoregions and ecozones in Canada (Sheppard et al. 2011). Generic "non-responsive" values were often applied in studies and models, as demonstrated in British Columbia's Agriculture Water Demand Model (AWDM) (van der Gulik et al. 2013). In the AWDM, a constant water-use value of 85 L of water per day (L day^{-1}) was assigned to lactating cows of which 65 L d^{-1} was attributed to drinking, 5 L d^{-1} to milking preparation and 15 L d^{-1} to pen and barn cleaning, milking system and bulk tank washout, and milking parlor washing. The value was applied regardless of the established influence on water-use from seasonal changes in temperature, variations in the composition of cattle diet (Beede 2005; Harner et al. 2013), or milking management system, i.e. difference in washwater use between tie-tall systems, parlour and robotic systems (House et al. 2014).

Canadian WFP studies were few in number and comparison of water-use results remained difficult due to differences in study methodologies, objectives, boundaries, scope and parameters. Arsenault et al. (2009) estimated ground and surface water-use for Nova Scotia confinement-base farms as 8.7 L kg^{-1} milk and pasture-based farms as 8.45 L kg^{-1} milk as part of a LCA assessment. The study did not consider water-use for crops or pasture, cattle use was limited to intake, and barn use included only cleaning of milk lines and bulk tanks. Data for drinking water was from an archived 2003 AAFC document with generic water requirements for pastured animals. The reliability or origin of the source data remains unknown. Cleaning water requirements were taken from a study by Cuthbertson et al. (1995) who surveyed 308 dairy producers and recorded washwater use for cleaning equipment based on supplier calculations. The data was considered the Ontario standard and was used to establish parameters and washwater production factors in the Ontario Ministry of Agriculture, Food and Rural Affairs' (OMAFRA) Nutrient Management and Nutrient Management 2 software programs; these free-access programs were developed to help farmers meet the requirements of government regulations and protocols relating to the management of materials containing nutrients including water (OMAFRA 2015).

Quantis, AGECO and CIRAIG (2012) also conducted a LCA-based study; but, the focus was on water-use in Canadian dairy production from the farm field to the processing plant. The LCI included green water incorporated into plants and blue water used for irrigation, drinking, cleaning and power generation. Grey water quantification excluded green sourced water. Results were highly variable ranging from 11 L H_2O kg^{-1} milk to 336 L H_2O kg^{-1} milk with a weighted national average of 20 L H_2O kg^{-1} milk: a range that highlights the diversity of Canadian dairy production. Crop production processes were estimated with an unspecified model using Ecoinvent (SCLCI 2010) data. Cleaning water was approximated as 15-20 L day^{-1} cow^{-1} for tie-stall and 25-30 L day^{-1} cow^{-1} for free-stall based on personal communication with an expert from the Fédération des producteurs de lait du Québec. Drinking water was calculated as 115 L day^{-1} for lactating cows, 25 L day^{-1} for heifers and 9 L day^{-1} for calves based on a 2010 AAFC report and expert consultation.

Another Canadian study by Brown et al. (2009) examined virtual water requirements in accordance with a study by Chapagain and Hoekstra (2003). Virtual water is equivalent to a WFP but refers strictly to the volume of water required to produce a product without reference to return flows, the type (green, blue or grey), origin (precipitation, surface or groundwater) or timing of water-use (Hoekstra et al. 2011). Brown et al (2009) determined the virtual water content of crops and livestock in British Columbia's Okanagan and Lower Fraser Valley water basins through calculation of water required for cattle intake, crop growth, feed preparation, and cleaning. The primary data source for cleaning and feed calculations came from the Agricultural Census (Statscan 2003), drinking water data came from British Columbia's Livestock Water Handbook (BCMAL 2006), and ET data came from crop coefficient values from Environment Canada. The virtual water requirement from feed, drinking and service water for dairy cattle was estimated at 32 628 m^3 $animal^{-1}$ $year^{-1}$ with feed water accounting for over 99% of the value. The virtual water content of dairy cattle at end of life span was estimated at

55 302 m^3 ton^{-1}. It is evident from this study that virtual water content results were not comparable to typical WFP results. Additionally, the study failed to provide the breakdown of data required to assess water-use efficiency at the farm-level.

Overall, reports relying on *in situ* measurements were limited with only two Ontario-based studies identified during the literature review. House et al. (2014) conducted *in situ* summer-time measurements over the course of three years (2011-2013) at 29 southern Ontario farms to evaluate washwater use under varying management systems. The data was collected for the purpose of updating the OMAFRA Nutrient Management software program. The results of the study have been largely incorporated into this study and are discussed in greater detail in Section 4.5.3. The second study was conducted over a twenty month period (May 2013 to December 2014) at 17 dairy farms dispersed throughout Ontario (Robinson 2015). The farms were of various sizes and provided a good cross-section of milking and housing systems, i.e. tie-stall, free-stall parlour and free-stall robotic. *In situ* measurements of total barn use (cattle consumption and milkhouse use) or milkhouse use were taken throughout the study period. Results provided insight into the differences in water-use between management systems with total water-use averages of 168.8 L d^{-1} cow^{-1} for free stall robotic systems, 134.6 L d^{-1} cow^{-1} for free stall parlours and 101.3 L d^{-1} cow^{-1} for tie-stall systems. The study also shed light on the influence of seasonal changes on water-use and the value of sustainable water management practices.

2.2. The Eastern Great Lakes and Hudson Lowlands Ecoregion

Ontario and Québec account for over 80% of dairy farms and over 70% of dairy cows in Canada (CDIC 2014) with an estimated 65% of these farms located in the

Eastern Great Lakes Hudson Lowland Ecoregion (EGLHLE) (AAFC 2014). As the predominate ecoregion for dairy in Canada (Wiken et al. 2011), the EGLHL region is an ideal environment for conducting *in situ* field, barn and animal-related measurements.

The EGLHLE is characterized by mid-latitude, humid continental climate with warm summers and cold winters. Mean annual temperatures within the region vary from $5^{o}C$ to $9^{o}C$ and the frost free period ranges from 120 to 170-d with areas closer to the Great Lakes having longer growing seasons (Wiken et al. 2011). The terrain is predominately rolling to level with clay and silt soils resulting from glacial and post-glacial scraping and deposits (Crins et al. 2009; Wiken et al. 2011; MDDELCC 2013). The climate and soil favour the production of crops required to satisfy the dietary demands of dairy cattle (Ouranos 2015).

2.3. Dairy Farming in the Eastern Great Lakes and Hudson Lowlands Ecoregion

Dairy farms in the EGLHLE are generally family operations with herds of approximately 60 cows excluding calves and heifers (Canwest DHI 2014; Valacta 2014). Holsteins are the breed of choice on 94% of farms (Canwest DHI 2014). The farms are year-round operations with tasks comprised of daily milking, feeding, cleaning of animals and equipment, reproduction management and stock rearing, and seasonal crop production (PLQ 2013b). In general, feed composition (Sheppard et al. 2011), housing style (Sheppard et al 2011; Canwest DHI/Valacta 2013), grazing, pasture (AAFC 2014), and manure management (Sheppard et al. 2011) are similar across the EGLHLE.

Crop selection in the ecoregion is determined by the agronomic conditions and is dominated by corn**,** leguminous alfalfa and soybean, and various grains (OMAFRA 2014). Adequate precipitation foregoes the need for irrigation (NRTEE 2010; CCA 2013). Field management practices are geared towards no till and conservation till with less than 25% of farms using conventional tillage (StatsCan 2014). Annual crops are fertilized with manure in early spring or early fall while perennial crops are generally fertilized from May to October, if needed. The ratio of solid manure to slurry used in the region is approximately 60:40 with a high percentage of farms storing solid manure in uncovered piles or bunkers (Sheppard et al. 2011). Planting of annual crops occurs late April to early May and perennial forages are seeded in early spring, as soon as the seedbed can be adequately prepared, or in summer following grain harvest. Harvesting of annual crops occurs in early fall while perennial crops are harvested 1 to 4 times per season (Brown 2009; PLQ 2013b).

As ruminants, cows have the ability to digest plant matter that is high in cellulose such as grass and hay; however, to produce quality milk and enable reproduction, the diet composition must satisfy the energy, protein, fibre, vitamin and mineral requirements that are specific to the life stage, weight and milk production of the animal (NRC-USA 2001; Jacobs and Hargreaves 2002). In the EGLHLE, crops selection has resulted in a diet which generally consists of total mixed rations comprised of corn silage (whole plants) and alfalfa (haylage or dry-form hay) originating from on-farm crops and off-site purchases. Smaller amounts of concentrated feed include mixed grains and oil seed forages (soybean) along with supplements, minerals and salt. Within a barn-based system, in which cattle are housed and provided with harvested forage (USDA-NRCS

2007), feedings may be as frequent as 7 times daily. In grazing systems, cows will consume multiple small meals daily over the course of 4 to 9 hours (DeVries 2013). Grazing practices in the ecoregion, however, are restricted to non-winter periods and are becoming less popular as producers convert to barn-confinement systems. Confinement systems are associated with increases in average milk production due to a reduction of temperature stresses and alleviate producer concerns relative to grazing regulations such as those restricting access to waterways (LPLQ 2013b; DFC 2015). Based on the 2006 *Farm Environmental Management Survey* of producers that employed grazing, approximately 65% used cultivated pasture and 60% implemented rotational grazing to improve and maintain pasture (AAFC 2014).

Traditional tie-stall barns account for 80% of housing in the ecoregion (Sheppard et al. 2011; Canwest DHI/Valacta 2013). Tie-stalls provide individual bedding stalls for each cow with free access to feed and water troughs /bowls (LPLQ 2013b; DFC 2015). Cows are milked by machines in their stalls with a pipeline system, generally situated 3 to 7 feet above the cow's udder, which provides vacuuming and conveyance of milk to bulk tanks (Reinemann 2007). Farms with larger herds, generally in excess of 100 cows, typically have a free-stall system in which the animals are housed freely with shared feed and water bunks. The system is less labour intensive with milking occurring in a central parlor that accommodates multiple cows and sends milk through milk lines directly to a central receiving jar for transport to the bulk tank (Reinemann 2007; CDIC 2013a). On tie-stall and free-stall parlor farms, cows are generally milked two times daily, morning and evening, and produce an average of 30 L milk d^{-1} (LPLQ 2013b; DFO 2014). Robotic milking systems may also be used with free-stall housing. Presently, robotics are used in approximately 4% of dairy farms in the ecoregion (Canwest DHI Valacta 2013; Valacta 2014); but, they are considered the future of the industry due to the increased flexibility in labor and management requirements, long term financial benefits, increased milk production and improved animal health (Rodenburg 2007, 2012; Valacta 2014;). These sensor-based management systems are capable of milking on an as-needed basis, as determined by the animal, and generally average 2.5 daily milkings per cow (Nixon et al. 2009; de Koning 2010). Robotic systems also adjust feed levels, perform teat cleaning, assess the overall well-being of dairy animals and provide relevant operations data to the farmer without the need of personal intervention (de Koning 2010). Regardless of the milking system, upon leaving the cow, milk must be cooled to a temperature of 10^{o}C within one hour, generally with the use of a water-based plate cooler, and transported to the bulk tank within two hours where it is kept between 0^{o}C and 4^{o}C until transport to the processing facility (CDIC 2013b; LPLQ 2013b).

Dairy farms in the ecoregion are subject to stringent federal, provincial, and industry regulations that govern standards of care and operations (NFACC/DFC 2009; FPLQ 2014). Farms are required to be licensed and adhere to supply management (quota) policies that ensure dairy production reflects the needs of the Canadian market. The quota system is overseen by the Canadian Dairy Commission and administered by provincial commodity marketing boards (e.g., Dairy Farmers of Ontario and Les producteurs de lait du Québec). Individual farms are allocated specific production quotas, expressed as kilograms of daily butterfat, which may fluctuate according to consumer demand. The quota system is designed to avoid overproduction of milk and is responsible for management and breeding practices at the farm-level that are geared towards maintaining consistency in herd sizes and milk production levels. The quota system, which also restricts dairy imports through tariffs, also ensures stable revenue without subsidies for producers and, a stable supply of milk and milk products for consumers (Lang 2014).

2.4. Water-Use in Field Crops

Crop growth is regulated by water availability; yields may be reduced or crops fail when too much water limits oxygen availability in the soil or a deficit restricts water and nutrient movement from the soil into the plant (Brouwer and Heibloem 1986; Allen et al.1998; Irmak 2009). Water used in crop production generally originates from precipitation, irrigation and capillary rise, the latter of which is often deemed negligible due to the depth of the water table (Li et al. 2008; Djaman and Irmak 2013). In Canada, crop water requirements are most often satisfied through precipitation. Irrigation is only required in approximately 3% of all croplands with 95% of this need occurring in the western provinces (CCA 2013). The EGLHLE, with a mean annual precipitation of 965 mm (Wiken 2011), presently has no need for irrigation in dairy feed crop production. Nevertheless, improving the efficiency of existing water-use in the ecoregion remains a concern with the availability of surface and ground freshwater being threatened by climate change, and the increasing use and pollution associated to a growing population (NRTEE 2010; Schreier and Wood 2013). With the anticipated competition for the resource and the expected implementation of user fees, farmers will need to ensure water-use efficiency for production of adequate, yet economically viable, milk supplies.

Water-use in crop production refers to water that is: (a) lost through evaporation from the soil and surface of the wet plant canopy; (b) lost through transpiration from the plant leaf stomata; (c) retained in the plant (Allen et al. 1998; Irmak 2009) and; (d) in relation to the WFP_{WFN} (Hoekstra et al. 2011), water polluted during cultivation that makes its way to waterways or other water stores. The standard method of estimating water-use in crop production, however, is quantification of evaporation and transpiration (ET). While water is vital to plant physiology, serving as a conduit for growth essential nutrients, plants retain less than 1% of the water taken up by the roots. Soil and canopy evaporation along with transpiration, the process which drives water movement between root intake and stomata output, account for the remaining consumption (Katerji et al. 2008; Irmak 2009). As a result, ET is considered synonymous with crop water-use. But, to assess water-use at the farm-level, water stored in the plant is an important component of the water balance, i.e. the crop moisture is cattle intake. As such, the difference in harvested moisture weight and feed dry weight will be considered in WatBal-Dairy.

Evapotranspiration varies from the field to global scale based on variation in the growing environment and crop genetics; specifically, annual variation in climate and weather, crop characteristics, soil characteristics and management practices (Allen et al. 1998; Irmak 2009; AARD 2013). Table 3 provides an example of seasonal ET measurements reported in the literature for the major forage crops of the EGLHLE, i.e. corn, soybean and alfalfa.

Table 3 Partial summary of seasonal evapotranspiration estimates for forage crops commonly grown in the Eastern Great Lakes and Hudson Lowlands Ecoregion.

Crop	Accumulated ET (mm)	Location	Reference
Corn	500-800	Global	Brouwer and Heibloem 1986
			Hsiao 2012 (FAO
	~ 650	Temperate climate	Hsiao 2012 (FAO)
	500-900	Humid climate	Osman 2013
	618-714	Nebraska	Suyker and Verma 2009
	690-746	Nebraska	Suyker and Verma 2009
	616-656	Nebraska	Suyker and Verma 2009
	481 / 579	Nebraska (2009/2010)	Djaman and Irmak 2013
	620 / 634	Nebraska (2009/2010)	Djaman and Irmak 2013
	488 / 508	China (2007/2008)	Li et al. 2013
	476 / 484	China (2007/2008)	Li et al. 2013
	368/ 591/ 558	Nebraska (2009/2010/2011)	Rees and Irmak 2012
	500-550	Alberta	AARD 2013
	558–762	Central Plains, USA	Shawcroft 1989
Soybean	450-700	Global	Brouwer and Heibloem 1986
	300-800	Global	Wani and Heng 2012 (FAO)
	330-760	Australia	Wani and Heng 2012 (FAO)
	330-760	United States	Wani and Heng 2012 (FAO)
	450-700	Humid Climate	Osman 2013
	355/ 558 / 541	Nebraska (2009/2010/2011)	Rees and Irmak 2012
	457 - 609	Central Plains, USA	Shawcroft 1989
Alfalfa	800-1600	Global	Brouwer and Heilbloem 1986
	<200 - >1000	Global (arid to well-watered)	Moot D 2012 (FAO)
	540-680	Alberta (three cuts)	AARD 2013
	812-1219	Central Plains, USA	Shawcroft 1989
	828 - 1136	Kansas	Klocke et al. 2013
	1470 / 1557 / 1161	Turkey (1995/1996/1997)	Benli et al. 2006

2.4.1. *Influence of Climate on Field Crop Water-Use*

Solar radiation, temperature and wind speed (up to a certain magnitude) are positively correlated to ET (Brouwer and Heibloem 1986; Irmak 2009). For example, in a temperate humid continental climate such as that found in the EGLHLE, daily ET for grass when no water restrictions exist would be 1-2 mm in cool temperatures (~10^{o}C), 2-4 mm in moderate temperatures (20^{o}C), and 4-7 mm in warm temperatures (>30^{o}C) (Allen et al. 1998). Increases in relative humidity have an inverse effect on ET with humidity reducing the potential contribution of ET to the temperature-dependent atmospheric saturation point (Allen et al. 1998; Osman 2013).

2.4.2. *Influence of Crop Characteristics on Field Crop Water-Use*

Water-use is also highly influenced by crop morphology; specifically, surface and sub-surface biomass (Brouwer and Heibloem 1986; Osman 2013). Plants with greater leaf biomass such as corn will generally have higher cumulative ET than more compact crops such as soybean (Allen et al. 1998). However, while perennial forage crops such as alfalfa have significantly less surface biomass than many annuals, cumulative ET will often be higher than annuals. This may be attributed to more extensive rooting systems that enable access to soil water that is typically beyond the reach of annuals, and the ability of existing stands to maintain and access early season water in the effective root zone which is often made unavailable to annuals through runoff and deep percolation (Putman 2010; Neal et al. 2012). Crop phenology also impacts the extent of ET through the length of the growing season and the period of maximum water-use. While development phases vary in length with crop, plant type, and species (Osman 2013), the greatest water-use for annuals generally occurs in the mid-season stage beginning with maximum leaf canopy and ending with the on-set of senescence. In Canada, the period will generally occur in late spring to early summer (Twerdoff at al. 1999). For perennial crops with multiple harvests, such as alfalfa, full canopy development generally occurs at the first signs of bloom in the early crop development stage (Agrimet 2015). Cuttings, however, usually coincide with or occur prior to full canopy development depending on the nutritional needs of cattle (Brown 2009), thereby limiting the extent of maximum ET and the period of senescence. Nevertheless, the extent of perennial water-use will generally exceed that of annuals due to an extended growing season (Moore 2005; Putman 2010).

In assessing the impact of water-use in crop growth, consideration must be given to the efficiency with which individual plants use water. Several formulas exist for determination of water-use efficiency (WUE) at the field level including:

(1) $WUE\ (mg\ CO_2\ mg^{-1}\ H_2O) = A_d / \sum_{h=1}^{24} E$

where A_d is the net daily canopy CO_2 uptake (mg m^{-2} s^{-1}), and E is the above canopy ET rate (mg $m^{-2}s^{-1}$) (Pattey et al. 2001).

(2) $WUE\ (kg\ DM\ ha^{-1} mm^{-1}) = Crop\ DM\ Yield\ /\ ET\ (water\ use)$

where Crop DM Yield is the dry matter yield of the crop (kg ha^{-1}) and ET is the above canopy ET (mm) (Sheaffer et al. 1988).

Equation (eqn) 2 is most often applied in agronomic studies (Hatfield et al. 2001; Katerji et al.2008), as it has greater practical application for the crop producer, i.e. results are useful in managing irrigation needs and ascertaining management practices to improve yield (Katerji et al. 2008). As such, reference to WUE in this study refers to kg DM yield ha^{-1} mm^{-1} of water-use.

Broadly, annuals will have better WUE than perennials; however, alfalfa is an exception and is considered to have high WUE based on the number of cuts, and the percentage of biomass harvested and utilized (Putnam 2012). In considering the common EGLHLE forage crops, there are few Canadian studies addressing WUE. Globally, as noted in Table 4, there is a wide range of WUE reported for corn, soybean and alfalfa. The range is related to differences in climate, the length of the growing season and management practices in the various study areas. Of note, while the use of forage crops with high WUE has obvious advantages with respect to water-use, the selection of these crops is not always feasible. Decisions as to the type of crop grown must be made with consideration to the nutritional needs of the cattle and farm finances.

Table 4 Published seasonal water-use efficiencies for corn, soybean and alfalfa.

Location	Corn Grain kg $ha^{-1}mm^{-1}$	Soybean kg $ha^{-1}mm^{-1}$	Alfalfa kg $ha^{-1}mm^{-1}$	Source	Comments
Lebanon	13.6 – 18.9			Karam et al. 2003	
		3.9 – 5.4		Karam et al. 2005	
Italy	8.2 – 11.7			Katerji et al. 1996	
		4.7 – 7.7		Katejri et al.2003	
France	16	5.5		Marty et al. 1975	
Western USA	8.8			Sadras et al. 2012	Rain-fed
China	28.4		28.3	Tingwu et al. 2005	
	6.7 - 13.3	5.1-5.4		Liu et al. 2013	
	12.4			Li et al. 2013	No mulch
	25.2			Li et al. 2013	With mulch
Turkey	3.16-15.31			Kiziloglu et al. 2009	Silage Corn
	4.75-15.04				Rain-fed / Irrigated
Australia	45.2-52.9			Neal et al. 2011a	Irrigated
			18.3 – 18.9	Neal et al. 2011b	
Global	6-23	6-10		Sadras et al. 2012	
Lethbridge, Ab			12.98 – 16.34	Attram 2014	1st cut
			12.09 – 15.66	Attram 2014	2nd cut
			0.48 – 4.24	Attram 2014	3rd cut
			11.71 – 13.03	Attram 2014	Season Cumulative

2.4.3. Influence of Soil on Field Crop Water-use

Soil properties impact the availability of water for crops and the extent of nutrient leaching and grey water production. Soils vary in their capacity to hold water based on texture (particle size), structure (pore space), organic matter (OM) content and underlying layers that restrict root growth and water movement (AAFC/OMAFRA 1997; Brown 2009; AARD 2013). Loam and loam blends are considered ideal for growing crops due to high water holding capacity, i.e., these soils offer the greatest plant available water as defined as the volume of water between the soil matric potentials of field capacity and permanent wilting point (AARD 2013) (Table 5).

Table 5 Soil-water relationships for different soil textures (AAFC/OMAFRA 1997; AARD 2013).

Soil Texture (particle size)	Infiltration Rate (mm hr^{-1})	Water Holding Capacity (mm m^{-1})	Estimate of Plant Available Water at Field Capacity (mm m^{-1} of soil)	Grey Water Impact
Sand (0.5 to 1 mm)	High <30	<100	75	High risk of Leaching
Sandy Loam	Medium 20-30	140	125	
Loam	Medium 10-20	180	150	
Clay Loam	Medium 5-10	200	167	
Clay (< 0.002 mm)	Low 0.1-5	190	117	Increased risk of Runoff

Coarser soils (sand) have large pore spaces, which promote a high infiltration rate and quicker movement of water beyond the root zone (AAFC/OMAFRA 1997; Hilliard and Reedyk 2014). With a low cation exchange capacity, these soils are more susceptible to nutrient leaching, particularly mobile anions such as nitrate (Lehmann and Schroth 2003); this increases the risk of groundwater pollution. Clay soils are generally viewed as being beneficial to agriculture because of their higher moisture-holding capabilities. High clay content, however, increases runoff of contaminants into surface and groundwater (Hilliard and Reedyk 2014). The presence of organic matter has a major impact on both ET and grey water production. While generally accounting for less than 5% of soil composition, organic matter improves a soil's structure which typically enhances infiltrability, increases water holding capacity and the extent of the rooting zone, and positively influences biological and chemical functions important to overall soil health (Brown 2009; Osman 2013).

2.4.4. Influence of Management Practices on Field Crop Water-Use

Management practices have the ability to improve the organic matter content of soil, effectively increase crop WUE, and reduce the risk of water contamination. For example, conventional tillage, in which surface residue is removed and the soil exposed, is associated with lower WUE due to increased evaporation, the oxidization and breakdown of organic matter, deterioration of the soil structure and increased erosion, runoff and leaching potential (McConkey et al. 2011; Osman 2013). In comparison, no-till results in consistently higher WUE as field residue acts as a barrier to reduce soil evaporation and improves yields through improvements in surface organic matter, water infiltration and overall soil ecology (Huggins and Reganold 2008; Eilers et al. 2010; Lal 2013). Additionally, the no-till residue diminishes the risk of erosion and runoff, and reduces leaching potential (Hatfield et al. 2001). Conservation tillage is the mid-point between conventional tillage and no-till; it is generally defined as any method that retains adequate residues to cover at least 30% of the soil surface. The practice is less disturbing than conventional tillage, reduces the erosion potential and enhances water retention (Huggins and Reganold 2008).

As a source of essential macro and micro-nutrients and organic matter, the application of manure is a valuable management practice that positively influences crop production and WUE (PPC 2004; Brown 2009). Raw manure is composed of organic materials including feces, urine, bedding, feed, and microorganisms, and inorganic materials including soil and water (SMA 2008). Depending on on-farm management practices, manure may be applied in solid (<80% moisture content), semi-solid (80-90% moisture content) or liquid (> 90% moisture content) format (PPC 2004). Solid manure has the greatest impact on soil organic matter due to the presence of the organic bedding component and higher resistance to leaching (PPC 2004; Tarkalson and Leytem 2009). The nutritional composition of manure varies greatly as a result of animal diet, number and age of animals, bedding materials, and the manure handling and storage systems (Magdoff and van Es 2000; Matsi 2012). Manure application must be managed to minimize the risk of surface and groundwater contamination. A failure to match plant requirements and existing soil nutrient availability with manure composition may result in over application; this may lead to the build-up of excessive nutrients and increase the pollution potential (Edmeades 2003; AAFC/OMAFRA 2005). Management plans must consider the nature of the soil, the method, and the timing of manure application. The likelihood of nutrient leaching increases: (a) when there is an elevated sand content and the presence of a high water table; (b) when application coincides with an intense rain event (AAFC/OMAFRA 2005; Hernandez and Schmitt 2012); (c) during the fall when root water intake is insignificant (van Es et al.2006; Brown 2009), and; (d) with liquid manure (Tarkalson and Leytem 2009). The risk of nutrient runoff for both liquid and solid manures is also enhanced by the failure to incorporate manure into the soil in a timely manner and by application onto frozen ground (Magdoff and van Es 2000; AAFC/OMAFRA 2005).

Crop management practices also influence the general condition and health of soil, and limit the risk of groundwater and surface contamination. Crop rotation, for example, may potentially improve yields, reduce the risk of weeds and pests, assist in maintaining or improving soil structure and organic matter content, and reduce soil erosion and runoff risks (Brown 2009; Dayegamiye et al. 2012). The inclusion of legumes such as alfalfa and soybean in a crop rotation is particularly beneficial. Legumes have the ability to fix nitrogen, seldom require additional nitrogen amendments and effectively minimize the risk of nitrogen leaching (Moot 2012). Crops following legumes benefit from stores of soil nitrogen remaining from legume residue; this lessens the need for additional amendment and creates cost savings (Crews and Peoples 2004; Brown 2009; Dayegamiye et al. 2012).

Management of drainage below crops is a major concern in limiting ground and surface water contamination. Natural drainage systems are not always sufficient and artificial tile drainage is often employed. Tile drainage systems may be uncontrolled with water flowing directly into a drainage ditch or controlled in which the system outflows may be increased during the spring to allow field drainage and decreased during the growing season to maintain water and nutrients in the soil. Overall, tile drainage has proven effective in reducing surface ponding, runoff, and soil compaction (AAFC/OMAFRA 1997). Several studies have also shown the benefit of controlled tile drainage in enhancing root development and yields of corn and soybean (Mejia et al.2000; Sunohara et al.2014).

2.4.5. Measurement of Field Crop Water-Use

There are a variety of methods to measure or estimate crop water-use. Table 6 provides a summary of available methods as noted by Rana and Katerji (2000). The choice of method is largely influenced by the end-goal of the project, the need for accuracy, logistics, temporal concerns and cost.

Table 6 Methods for measurement and estimation of evapotranspiration (ET) from Rana and Katerji (2000).

	Approach	Method
ET Measurement	Hydrological	Water balance
		Lysimeters
	Micrometeorological	Energy balance and bowen ratio
		Aerodynamic method
		Eddy covariance
	Plant physiology	Sap flow
		Chamber system
ET Estimation	Analytical	Soil-Crop growth models
	Empirical	Crop coefficient methods (formula)
	Empirical	Soil water balance modelling

For the broad-scale calculation of field water-use, such that required to improve the sustainability of dairy production in Canada (NTREE 2010; CCA 2013), analytical modeling provides the most viable option. *In situ* calculation methods are both spatially and financially prohibitive while empirically estimating crop ET is limited by a lack of crop- and region-specific parameters for this method. The water balance method also provides a viable option for population of the ET parameter when analytical modeling estimates are unavailable. However, the effectiveness of the water balance method in calculating ET will depend on the ability to accurately calculate or estimate water-use for all flow and storage parameters in the general water balance eqn 3. Some measurements are often difficult to obtain (Zhang et al. 2002) and assumptions may not always accurately reflect site-specific water-use. For example, capillary rise, runoff and deep percolation has been reported as negligible or non-existent (Rana and Katerji 2000; Zhang et al.2002; Li et al. 2008; Katerji et al.2008; Gervais et al. 2012) resulting in a calculation of ET through a simplified equation (eqn 4) (Li et al. 2008; Gervais et al. 2012). But, in a DNDC simulation of cereal grown in sandy loam soil in Eastern Ontario, leached water exceeded and runoff equalled approximately 50% of the annual accumulated ET (Vergé et al. 2015).

General field water balance equation

$$ET = P + I + CR + AW - DP - R \pm \Delta S \quad (3)$$

where ET is evapotranspiration (mm), P is precipitation (mm), I is irrigation (mm), CR is capillary rise (mm), AW is added water including water in manure or mixed with pesticides, insecticides and fungicides, DP is deep percolation (mm), R is runoff (mm), and ΔS is change in soil moisture (mm).

Simplified field water balance equation

$$ET = P + I - \Delta S \quad (4)$$

where ET is evapotranspiration (mm), P is precipitation (mm), I is irrigation (mm), and ΔS is change in soil moisture (mm).

2.5. Water-Use for Confined Animals

2.5.1. Water Inputs to Cattle

Cows have the greatest water requirement per unit of body mass of all terrestrial animals: a requirement needed to maintain life processes and satisfy the 87% water content of milk (Beede 2005). Water requirements are met through free intake (80-90%)

and moisture in feed (10-20%) (Beede 2005; Harner et al. 2013). Intake quantities vary with the life stage of the cattle, size, environmental factors and milk production. Based on Ontario provincial guidelines, the typical daily water intake (drinking) for the EGLHL is: 9 L for calves (1-4 months); 25 L for heifers (5-24 months); 41 L for dry cows and 115 L for lactating cows (Ward and McKague 2015).

Management decisions such as diet can significantly impact water intake. The percentage of dry matter in feed and the amount of dry matter intake (DMI) by cattle have significant influence on free water intake (FWI) and milk production (Murphy et al.1983; Khelil-Arfa et al. 2012; Appuhamy et al. 2015). Studies have shown that a decrease in the dry matter content of feed will decrease FWI; but, total water intake will remain constant due to the higher ration moisture content. An increase in DMI, however, will increase FWI while both total water intake and milk production will decrease (Holter and Urban 1992; Beede 2005; Olkowski 2009; Khelil-Arfa et al. 2012).

To a lesser extent, FWI is also impacted by dietary composition factors including the percentage of concentrate (grains), amount of crude protein, ash, fibre, sodium and proteins (Murphy et al 1983; Holter and Urban 1992; Appuhamy et al. 2014; Spellman 2015). Murphy et al. (1983) found that daily FWI increased by 0.5 kg for every 1g increase in sodium while Appuhamy et al. (2015) reported that a 3% increase in crude protein resulted in a FWI increase of 5.9 ±2.2 kg d^{-1}.

Temperature is also a strong determinate of FWI and may negatively influence milk yields (Murphy et al.1983; West 2003; Olkowski 2009). In early stage lactation, FWI has been shown to increase at a rate of 1.2 kg $^{o}C^{-1}$ from the minimum ambient temperature based on a temperature range of 8 ^{o}C to 19 ^{o}C (Murphy et al. 1983). The rate of increase in FWI, however, is notably higher when temperatures rise above the thermoneutral zone (5 ^{o}C to 25 ^{o}C). McDowell and Weldy (1967) noted that above 32 ^{o}C, FWI was 2 to 4 times greater than intake in the 2^{o}C to 10^{o}C temperature range (quoted in Beede 2005). While increased water intake is generally positively correlated to milk yield, under high heat conditions, milk production will remain constant or decrease in spite of the increased fluid intake (Olkowski 2009; Key et al. 2014).

Increased FWI has also been associated with elevated water temperature (Anderson 1985 quoted in Beede ; Wilks et al. 1990); interestingly, however, a Canadian study of lactating Holsteins and Jerseys showed that, in spite of increased water intake, there was no notable effect on milk production (Osborne 2001).

Poor quality water decreases FWI while increasing the health risks and reducing milk yields. Most farms in the EGLHLE currently rely on private wells for their water supply and conduct regular testing to ensure water quality meets drinking and cleaning standards (Mongeion 2012).

2.5.2. Quantification of Cattle Water Inputs

The determination of total water intake requires measurement or estimation of FWI, DMI, and the dry matter % or moisture content % of the animal's feed. On a farm-to-farm basis, *in situ* measurement of FWI is not feasible. However, *in situ* measurement of cattle water intake with flow meters on a smaller-scale may be used in the assessment and identification of empirical models (equations) that will satisfy broad-scale measurement. FWI regression equations (eqn 5-11) from existing literature reflect the most relevant factors influencing FWI based on the purpose and results of the cited studies. Most of the listed equations predict FWI for lactating Holsteins and may have limited application to other life-stages. Use of certain equations may also be limited by the availability of required input data. Of these equations, the National Research Council (NRC-USA) (2001) recommended use of the 4 variable regression model (eqn 5) developed by Murphy et al. (1983) (Harner et al. 2013).

(5) (A) **Four Variable Regression Equation (Early Lactating Holsteins)**

FWI = 16 + (1.58 × DMI) + (0.90 × MY) + (0.05 × SodIntake) + (1.2 X minT)

(6) (A) **Two Variable Regression Equation (Early Lactating Holsteins)**

FWI = 22.96 + (2.38 × DMI) + (0.64 ×MY)

(7) (B) **Three Variable Regression Equation (Dry Holsteins)**

FWI = -10.34 + (0.23 × DM) + (2.21 × DMI) + (0.039 × CP (% DM)^2

(8) (C) **Five Variable Regression Equation (Mid-Lactation Holsteins)**

FWI = (1.54 × DMI) + (1.33 × MY) +(0 .89 × DM) + (0.57 × minT) – (0.30 × rainfall) – 25.65

(9) (D) **Five Variable Regression Equation (Lactating and Dry Holsteins)**

FWI = 77.6 + (3.22 × DMI) + (0.92 × MY) + (0.83 × DM) + (-0.28 × CONC) + (0.037 × BW)

(10) (E) **Modified Kertz Equation**

TWI = (4 × DMI) + KG of 4% FCM + 25.6
FWI = TWI – RWI
Where: 4% FCM = (0.4 × MY) + 15 × (MY × FCM AS A DECIMAL)
RWI = DMI/DM ×MC

(11) (F) **Estimation for Heifers**

FWI = BW /100 × 3.78

where BW is body weight (kg); CONC is proportion of concentrate(g) in diet (%), CP is crude protein in DM (%); DM is dietary dry matter (g) (%); DMI is dry matter intake (kg/day); FCM is fat corrected milk; FWI is free water intake (kg/day); MC is moisture content (%); minT is minimum temperature (ºC); MY is milk yield (kg/day); RWI is ration water intake (kg/day); SodIntake is sodium intake (g/day); TWI is total water intake (kg/day).
(A) Murphy et al. 1983; (B) Holter and Urban 1992; (C) Cardot et al. 2008; (D) Khelil-Arfa et al. 2012; (E) Adams and Sharpe 1995 (F) Looper and Waldner 2002.

DMI values are generally required for calculation of FWI, cattle ration water intake (RWI), as well as cattle outputs. DMI may be estimated through dynamic models (Ellis et al.2006) or empirical models such as eqn 12-15 (Kertz et al. 1991; Holter and Urban 1992; Holter et al. 1997; NRC-USA 2001). Eqn 14 and eqn 15, the “As Fed” method (USDA-NOP 2011), provide the simplest and most practical method of determining DMI when feed quantities and the dry matter % or moisture content % of the feed are known. In lieu of firsthand knowledge of the actual dry matter % or moisture content %, values may also be based on general assumptions or retrieved from references such as the *United States-Canadian Tables of Feed Composition* (NRC-USA 1982).

National Research Council recommended DMI equation
(NRC-USA, 2001)

(12) $DMI = (0.372 \times FCM + 0.0968 \times BW^{.75}) + (1 - e^{(-0.192 \times (WOL + 3.67))})$

where FCM is fat corrected milk, BW is body weight (kg), WOL is the week of lactation, and $1 - e^{(-0.192 X (WOL + 3.67))}$ adjusts for the stage of lactation.

McGill University Equation
(McGill, N.D.)

(13) $DMI (\% \text{ of } BW) = 4.048 - 0.00387 \times BW + 0.0584 \times 4\% FCM$

where BW is body weight (kg) and 4% FCM is equal to (0.4 × actual milk yield in kg/day) + (15 × milk fat in kg/day).

USDA-NOP "As Fed" Calculation for DMI and RWI
(USDA-NOP, 2011)

(14) $DMI = FT \times DM (\%)$ or $DMI = FT - RWI$

where FT is the quantity of daily feed by type (kg), DM (%) is the percentage of the dry matter content of the feed and RWI is ration water intake as per Equation 15.

(15) $RWI = FT \times MC (\%)$

where RWI is ration water intake, FT is the quantity of daily feed by type (kg), and MC (%)* is the percentage of the moisture content of the feed.

* DM or MC of feed may be determined through the several drying methods. MC expressed as a percentage of total weight is:

$MC (\%) = (\text{Wet Weight} - \text{Dry Weight}) / \text{Wet Weight} \times 100$

$DM (\%) = \text{Dry Weight} / \text{Wet Weight} \times 100$

2.5.3. *Water Outputs from Cattle*

Cattle lose water through milk production, urinary and fecal excretions, saliva, and respiratory cutaneous water. Milk is composed of 87% water while as-excreted manure (urine plus feces) from lactating cows has an approximate 87.5% water content (Khelil-Arfa et al. 2012). The water content of excretions from heifers and dry cows is approximated at 83% to 87% (ASAE 2005). The general partitioning of water output based on total water input for lactating dairy cattle, as reported by the NRC-USA (2001), is found in Table 7. This partitioning will vary with genetics, stage of life, health, diet and climate. For example, Holter and Urban (1992) report urine output ranging from 4.5 to 35.4 L day^{-1} for a lactating cow producing 35.4 kg^{-1} milk day^{-1} and 5.6 to 27.9 L day^{-1} for a dry cow (quoted in NRC-USA 2001).

Table 7 Relative percentage of water loss by output in dairy cattle from NRC-USA (2001).

Nature of Loss	Quantity of Water Loss	Estimate of Total Water Intake	Source
Milk Secretions	33 kg d^{-1}	34%	Holter and Urban, 1992;
		29%	Dado and Allen, 1994
		26%	Dahlborn et al., 1998
Feces		30-35%	Holter and Urban, 1992; Dahlborn et al., 1998
Urine		15-21%	Holter and Urban, 1992 Dahlborn et al., 1998
Saliva/respiration	20 kg d^{-1}	18%	Holter and Urban 1992

Total water intake and DMI are the largest influences on water outputs with a strong positive correlation to milk production and feces and urine excretions (Murphy 1992; Weiss 2004; ASAE 2005; Khelil-Arfa et al. 2012). Diet composition also influences the dynamics of water loss. Higher dietary dry matter (fibre) is linked to an overall increase in total manure production (Weiss 2004; Khelil-Arfa 2012), while higher crude protein intake is strongly associated with increased urine output (Murphy 1992; Nennich et al. 2006; Khelil-Arfa 2012).

Temperature is a strong determinate of the extent and nature of water loss from the animals. McDowell and Weldy (1967) reported that a 12^{o}C rise in temperature from 18^{o}C increased FWI by 29%, and resulted in increased urine, perspiration and respiration outputs of 15%, 59% and 50% respectively. Fecal water loss, however, declined by 33% (quoted in NCR-US 2001). As a result, respiratory cutaneous water losses contribute significantly to the cattle output water balance. In thermoneutral conditions (5^{o}C to 25^{o}C), respiratory cutaneous water losses were estimated at 18% by Holter and Urban (1992). For a cow producing 35 kg day^{-1} of milk, this represented respiratory cutaneous water loss of approximately 20 kg day^{-1}. Appuhamy et al. (2014) supported these findings with an estimated respiratory cutaneous water loss of 18 kg day^{-1} for a cow producing 35 kg day^{-1} of milk. Silanikove et al. (1997) noted that in mean temperatures of 12 to 14 ºC, in addition to a strong positive correlation between respiratory cutaneous water and temperature, increased respiratory cutaneous water was also positively correlated to DMI. The increased dietary intake was attributed to higher metabolic energy demands associated with thermoregulation of body temperature. Silanikove et al. also noted a negative correlation between respiratory cutaneous water and milk production. Interestingly, reduced yields were attributed to the loss of essential milk production ions (chloride and potassium) through sweat.

2.5.4. Quantification of Cattle Water Outputs

Quantification of water flows to milk is generally calculated using known milk outputs and eqn 16. For other outputs, *in situ* measurements are preferable but are spatially and temporally impractical, particularly when dealing with pastured cattle. The use of established tabulated values is an option although care must be taken to ensure the selected values are not obsolete as a result of changes in genetics, performance potential and diet (ASAE 2005). Numerous empirical models exist for urine, fecal water and respiratory cutaneous water calculations. Many equations rely on inputs from *in situ* measurements or chemical analyses making broad-scale application unfeasible; however, Eqn 16 - 23 are practical in nature, relying on data inputs which are generally known at the producer level.

Milk Water

(16) (D) $MW = MY \times 0.87$

Fecal Water

(17) (A) Lactating Cows $FW = 8.84 + (2.18 \times DMI) - (0.24 \times DM) - (0.23 \times MY)$

(18) (A) Dry Cows $FW = 5.52 + (1.32 \times DMI) + (0.038 \times DM)$

(19) (B) Dry and Lactating $FW = FDM \times [(100 - fDM)/fDM]$

Where FDM is calculated from: $FDM = 0.43 \times DMI - 1.98 \times 10^{-5} \times CPf^2 - 2.30$

Urinary Water

(20) (C) Lactating Cows $U_E = (BW \times 0.017) + 11.70$

(21) (F) $U_E = 12.3 + (0.72 \times DMI) - (0.11 \times CS)$

(22) (B) Dry and Lactating $UW = -2.2 \times 10^{-4} \times CPf^2 + 0.88 \times DMI + 0.19 \times CPf + 9.30 \times 10^{-4} \times CPc^2 - 20.6$

Total Manure Water

(23) (F) Lactating Cows $M_E = 7.6 + (3.0 \times DMI) - (0.11 \times CS)$

(24) (C) Dry Cows $M_E = (BW \times 0.022) + 21.844$

(25) (C) Heifers $M_E = (DMI \times 3.89) - (BW \times 0.029) + 5.64$

Dry Matter Excretions

(26) (C) Lactating Cows $DM_E = (DMI \times 0.35) + 1.017$

(27) (C) Dry Cows $DM_E = (DMI \times 0.18) + 2.73$

RCW Loss

(28) (E) $RCW = TWI - MW - UW - FW$

where: BW is the average live body weight; C_{CP} is the concentration of crude protein of the total ration (g g^{-1} of feed day^{-1}); CPc is the dietary content of crude protein ingested in concentrate (g kg^{-1} DM); CPf is the dietary content of crude protein ingested in forage (g kg^{-1} DM); CS is the % of corn silage in forage DM; DM is dietary dry matter (g) (%); DM_E is the actual fecal matter plus urine dry matter (kg day^{-1}) with urine dry matter estimated at 4.5% based on a specific gravity of 1.038 g ml^{-1}; DMI is dry matter intake (kg day^{-1}); FDM is fecal dry matter excreted (kg day^{-1}); fDM is dry matter content of the feces (%); FW is the fecal water content; M_E is fecal excretion plus actual urine excretion (kg day^{-1}); MF is milk fat (g g $milk^{-1} day^{-1}$); MW is the quantity of water in milk (kg); MY is the milk yield (kg day^{-1}); RCW is respiratory cutaneous water; TWI is total water intake (kg day^{-1}); U_E is the volume of urine excreted (L day^{-1}), and: UW is the water content of urine (kg day^{-1}) (A) Holter and Urban 1992; (B) Khelil-Arfa et al. 2013; (C) ASAE 2005; (D) Appuhamy et al.2014; (E) Silanikove et al. 1997 (F) Weiss 2004.

2.6. Pasture / Grazing Water-Use

From a water-use perspective, the pasture environment and associated grazing practices are essentially an amalgamation of the field and cattle environments with the variables influencing field crop and animal water-use remaining relevant. Within the pasture environment, DMI and FWI are largely influenced by: (a) the quantity, quality and palatability of the grass/grain mixture; (b) selective grazing practices that contribute to the increased intake of feed that is typically high in energy and dietary protein, and (c) the extent of supplemental feed (Jacobs and Hargreaves 2002). Holden (1993) determined that there was a 4.2 kg decrease in pasture intake for every kg of corn consumed. DMI is also influenced by the harvesting efficiency of the animal with the time expended on grazing, the bite rate and bite size all positively correlated to feed intake (Jacobs and Hargreaves 2002). FWI consumed by pastured cattle is also significantly influenced by environmental conditions with a strong and significant correlation between FWI, temperature and hours of daylight and a significant negative correlation with precipitation (Castle and Watson 1973).

2.6.1. Measurement of Pasture and Grazing Water-Use

The measurement of pasture water-use, (ET), is consistent with practices established for field crop growth. However, the measurement of cattle water-use presents a unique challenge in that, unlike confinement systems, there is generally no monitoring or control of inputs or outputs in the pasture environment. The key to estimating required pasture water intake and outputs centers on the calculation of DMI. With knowledge of DMI, the equations such as those previously presented in Section 2.5 for FWI, fecal and urinary outputs may be evaluated and employed. But, the inability to adequately and efficiently estimate pasture DMI has long been considered detrimental to nutritional management (Cordova et al. 1978; Macoon et al. 2003; Undi et al. 2008), and remains problematic to the goals of this study. On-farm measurements (i.e. herbage disappearance, pulse dose marker methods) (Macoon et al. 2003) are time-consuming and logistically impractical, while many empirical methods are limited due to the nature of the input requirements. Eqn 29 (Minson and McDonald 1987), which was developed for beef cattle and requires accurate average weight gain estimates, and eqn 30 (USDA 2010), provide the best options for calculation of DMI from producer-based information or existing standards. Eqn 30 requires knowledge of dry matter demand and the dry matter content of any supplemental feeds. Dry matter demand refers to the expected DMI for an animal class based on stage of life, stage of production and body weight. Dry matter demands are generally extracted from existing requirement tables such as those provided by the USDA National Organic Program (2010).

Minson and McDonald (1987)

(29) $$\text{DMI} = (1.185 + 0.00454\text{BW} - 0.0000026\text{BW}^2 + 0.315\text{ADG})^2$$

where BW is body weight (kg), and ADG is average daily gain (k day^{-1})

USDA-NOP DMI Estimation (2011)

Step 1: Calculate Dry Matter Demand (DMD) by:
(a) reference tables; or
(b) calculation with:

(31a) $$\text{DMD} = \text{BW} \times (\text{DMI\%BWV}/100)$$

where BW is average body weight by class (kg), and (DMI%BWV/100) is the dry matter intake body weight value (%)/100 kg

Step 2: Calculate Dry Matter Intake of Supplemental Feed (When Required)

(31b) $$\text{DMI} = \text{FT} \times \text{DM}\ \%$$

where FT is the quantity of daily feed by type (kg), and DM is the dry matter content of the feed (%)

Step 3: Calculate Pasture Dry Matter Intake (PDMI)

(31c) $$\text{PDMI} = \text{DMD} - \text{TDMI}$$

where DMD is the dry matter demand (kg) and TDMI is the total dry matter intake from supplemental feed.

2.7. Water-Use in the Barn

While dairy quality standards stipulate minimum cleaning criterion and protocols (AAFC/DFC 2010), the volume of washwater generated is limited by the ability to properly manage waste as per provincial government legislation such as Ontario's *Nutrient Management Act, 2002* (House et al. 2014). Equipment cleaning is critical in the dairy industry to ensure the purity of the milk product. Potable water, free of *Escherichia coli* (E coli) and other coliforms, is required for sanitation, rinsing, detergent washing, and acid rinsing (House et al. 2014). The quantity of water used varies according to herd and building size, milking frequency, the milk management system, the degree of water reuse and other miscellaneous uses including cow cooling (Harner et al. 2013; House et al. 2014). In general, estimates provided by House et al. (2014) indicate that tie stall barns will use a maximum amount of water of 64.4 kg cow^{-1} day^{-1}, parlor systems 84.5 kg cow^{-1} day^{-1}, robotic brush teat cleaning systems 72.6 kg cow^{-1} day^{-1} and robotic water teat cleaning system 84.5 kg cow^{-1} day^{-1}. These numbers may be reduced by approximately 45 kg cow^{-1} day^{-1} if the water used in the heat exchanger that cools milk (plate cooler) is recycled, and another 11 to 17 kg cow^{-1} day^{-1} may be saved in parlor and robotic systems when milk equipment water is recycled for parlor wash down. House et al. (2014) did not include animal cooling water in their estimates. Estimates for animal cooling water (sprinklers, misters) show a high degree of variability depending on the system type, coverage area and the period of use (Harner et al. 2013).

2.7.1. Waste Water and Manure Management

Waste water, cattle excrements and bedding waste are among the primary concerns facing dairy producers due to potential environmental and health threats (Bourque and Koroluk 2003; AAFC/OMAFRA 2005). Waste management systems must ensure environmental protection while maximizing use of manure nutrients in crop production. Points of primary consideration in designing and implementing a waste management system include the volume of waste produced, the collection system, the method of transport to the point of storage, the storage structure, the nature of transportation to the application site and application scheduling (AAFC/OMAFRA 2005). In general, waste and manure management is influenced by the nature of dairy operations. Tie-stall operations tend to employ a solid manure management system in which manure is mixed with bedding. Barns commonly have gutters to collect waste and rely on augers, conveyor belts or manual labour for transport to covered or uncovered exterior stockpiles or silo pits. Uncovered manure piles, which are common in the EGLHLE, have a high potential for contaminated runoff. Strict regulations are in place, however, to control pollution of nearby waterways (AAFC/OMAFRA 1997; Sheppard 2011). Solid manure is generally disposed of through land application. Milkhouse wash water in tie-stall systems, contaminated with detergents, concentrated phosphoric acid and spilled milk, is most often drained into a treatment system that includes a septic system (Hawkins and Barkes 2014). By law, storage and treatment systems must be designed to prevent contamination of surface and groundwater; however, there is always an underlying risk of grey water production.

Free stall / parlour operations may also use solid manure management systems (US-EPA 2012), but along with robotic operations, are generally associated with liquid or semi-solid waste management. In these systems, manure is commonly collected with or without solid waste through slatted floors, mechanical scraping or flushing systems and combined with washwater and other liquid waste in earthen, steel or concrete storage containers until pumped into tanks for field application (Bourque and Koroluk 2003; US-EPA 2012). The risk of freshwater contamination from liquid storage is also minimized through strict regulation of design and upkeep.

2.7.2. *Measurement of Barn Water-Use and Waste*

The installation of meters provides the simplest method of determining water-use in the barn environment, but broad-scale application is not feasible. Empirical models provide a viable option for water-use calculations providing the equations are responsive to the diversity of individual farm practices and milking system lay-outs. Tie-stall operations are typical in nature enabling reasonable estimation of per cow, bulk tank and plate cooler water-use based on animal numbers and production. However, water-use in free stall / parlour milking systems varies due to differences in the number of animals occupying the same area, cleaning and recycling practices (House et al. 2014). The OMAFRA Nutrient Management Software Program (2015), an empirical model recently updated by House et al. (2014), provides a notable degree of responsiveness relative to the number of animals, type of milking system, recycling practices and equipment. The model is discussed in greater detail in Section 3.3.3.

2.8. Eddy Covariance Method

The ability of the alfalfa algorithm in DNDC to provide accurate simulations of ET and NEE will be validated with *in situ* eddy covariance measurements of ET and NEE. NEE is the difference between CO_2 uptake via net primary production and CO_2 loss via respiration (Kirshbaum et al. 2001). The eddy covariance method is considered one of the most direct and reliable methods of quantifying both CO_2 and water vapour exchange between the atmosphere and agricultural fields (LI-COR 2013; Baldocchi 2014). Flux measurements represent integrated areas of 10 ha typically at a 30-min time-step quasi-continuously for the duration of the measurement period with no disturbance to the vegetation or the soil beyond the area with the infrastructure used to support the instruments (Baldocchi 2014).

In this method, trace gas and water vapour fluxes in the surface boundary layer are calculated using the covariance of fluctuations in vertical windspeed and the concentration of the target gas (Baldocchi 2003; ; Aubinet al. 2012; Burba 2013) (eqn 31 and eqn 32). This requires turbulent conditions.

(31) $$F = \overline{Pa}\,\overline{w's'}$$

where F is flux, $\overline{Pa}$ is the mean product of air density, $\overline{w'}$ is vertical wind speed, and $\overline{s'}$ is the dry mole fraction or mixing ratio of the target gas.

(32) $$LE = \lambda E = \lambda \frac{M_w/M_a}{P} \rho_a \overline{w'e'}$$

where LE is latent heat flux (H_2O flux in energy units expressed in W m^{-2}), $\lambda \frac{M_w/M_a}{P}$ is the latent heat of vaporization, ρ_a is the density of air, and $\overline{w'e'}$ is the covariance of the turbulent fluctuations of the vertical wind component w and the concentration of water vapor e (mmol mol^{-1}).

Over bars indicate time averaging and the primes are indicative of fluctuations from the mean.

Eqn 31 and eqn 32 use Reynold's averaging and the assumption that air density fluctuations and mean vertical flow are negligible over horizontal terrain (Baldocchi 2003; Burba 2012). Measurements of positive net flux indicate that the study site is a source of the target gas while negative fluxes indicate the surface is a sink (Burba 2013). Latent heat fluxes are converted to ET using the using the latent heat flux and density of water.

While technical advances have been made over the past 40 years, the accuracy of eddy covariance flux measurements remains affected by random and systemic bias and sampling and theoretical errors related to measurements in non-ideal situations (Baldocchi 2003; Aubinet et al.2012; Burba 2013). The greatest accuracy in the method occurs when measurements are taken over flat terrain, in steady environmental conditions and in sites where vegetation extends upwind for 250 m (Baldocchi 2003; Burba 2013). Even in ideal conditions, however, it is generally accepted that there is a failure to achieve energy balance closure on the order of 20 to 30%, i.e. the sum of latent (λE) and sensible heat exchange fall short of available energy (Leuning et al. 2012; Wohlfahrt and Widmoser 2013). This bias may be corrected providing: (a) detailed attention is given to available energy measurements including correct estimation of the energy storage in soil, air and biomass below the equipment measurement point, and; (b) careful correction of eddy covariance data processing errors (Leuning et al. 2012). Other problems with data accuracy may also occur with the most common sources of error being: frequency response, spiking and noise in data, accurate measurement of density fluctuations, sensor time delays and data gap filling routines (Burba 2013). Advances in eddy covariance data processing software (EddyPro v. 5.2.1, LI-COR Inc 2015), however, have removed most of the complexity associated with error correction.

2.9. Denitrification and Decomposition (DNDC) Model

DNDC was released in 1992 to simulate soil carbon and nitrogen dynamics in American agricultural soils on a daily time-step (ISEOS 2012; Gilhespy 2014 et al.). For over 20 years, the model has been used and modified worldwide to accommodate different ecosystem processes including crop growth and water movement (Gilhespy et al. 2014). Modifications relating to crops and water in DNDC include: (a) the creation of an empirical plant growth sub-model in 1994; the development of a crop sub-model in 2002 that enabled coupling of crop growth with soil biogeochemical and climatic parameters, and facilitated simulation of most processes in the carbon, nitrogen and water cycles in agricultural settings, and; (c) the addition of code to improve estimates of soil evaporation under variable residue levels (Smith et al. 2010). These modifications have all been incorporated into the primary DNDC model (Gilhespy et al. 2014). Additionally, the most recent version (DNDC v. 9.5) features improved crop growth simulations and hydrological features (Gilhespy et al. 2014).

DNDC is a complex two-component model that incorporates hundreds of deterministic equations based on the classic laws of physics, chemistry, and biology, and empirical equations generated from research studies, to simulate geochemical and biochemical reactions (ISEOS 2012; Qin et al. 2013). The first component consists of the soil climate, crop growth and decomposition sub-models which are driven by four ecological drivers: climate, soil, vegetation and management practices. The second consists of the nitrification, denitrification and fermentation sub-models which are driven by simulated soil environmental factors to predict trace gas fluxes from the plant-soil system (ISEOS 2012).

The complexity of DNDC is a result of the high degree of interaction (drive and effect) between the various sub-models. For example, empirical crop growth in DNDC is driven by the accumulation of growth degree days (accumulated temperature relative to 0ºC), with water and nitrogen demand and uptake estimates from the soil climate submodel serving as limiting factors to potential growth (Kröbel et al. 2011; ISEOS

2012). Daily biomass calculations are based on cumulative nitrogen uptake and estimated plant carbon/nitrogen ratios which is partitioned into root, grain and shoot (leaf and stem) biomass as dictated by fractions embedded in the algorithm (Kröbel et al. 2011). Through empirical relationships, crop growth estimates are instrumental in regulating simulations of ET, soil moisture and carbon regimes (ISEOS 2012). In view of the complexity of DNDC operations, the quality of simulations is dependent on the accuracy of the input data for the four aforementioned ecological drivers. The DNDC User Manual (ISEOS 2012) provides detailed information relating to inputs and outputs for site (farm) and regional levels. Input and outputs for site level simulations are noted in Table 8.

Table 8 Description of DNDC inputs and outputs (ISEOS 2012).

Input Categories	• climate, soil, and farming management practices including current and historical cropping practices, crop details, tillage, fertilization, manure amendment, irrigation, grazing and grass cutting
Mandatory Inputs	• site location, climate (temperature, precipitation, windspeed, radiation, humidity), bulk density, soil organic carbon, texture and pH in surface soils • other inputs may be defaulted
Simulated Output Categories	• daily climate, crop growth, field management, grazing, soil climate, soil carbon, soil nitrogen, soil phosphorus and soil water • annual summations of crop growth and yield, soil carbon and nitrogen fluxes and water balance for the study site
Study Related Outputs	• daily precipitation, potential evapotranspiration, actual evapotranspiration, carbon flux, crop yield, manure application rates, grazing cattle input, urine and dung output, soil moisture, soil water to 50 cm, soil water below 50 cm, runoff, leaching, crop water demand

Modeling simulations are generally associated with uncertainties stemming from the model itself including defects in the scientific basis, structure or algorithms, and errors or omissions in the input data (ISEOS 2012). The validity of DNDC's crop water simulations, however, has been tested in several studies. In a comprehensive *in situ* water, rice and wheat field experiment in China, and a corn field experiment in the USA, both the DNDC model and the former Crop sub-model provided soil moisture, crop growth, and soil carbon and nitrogen dynamics that correlated well with measured data (Zhang et al. 2002). A 2009 Illinois based study of a typical corn and soybean agro-ecosystem in tile drained fields found that DNDC (DNDC82a) was able to make accurate predictions of crop yield and drainage water flux (David et al. 2009). In a Swiss study, DNDC performed well relative to eddy flux measurements when providing simulations of water vapour fluxes and cumulative fluxes (CO_2 and H_2O) over a 5 year period for multiple crops (winter wheat, winter barley, winter rapeseed, potato and cover crop). In the same study, DNDC also proved effective in simulating NEE under rising temperature conditions (Dietiker et al. 2010). Kröbel et al. (2011) determined that with a minor algorithm modification to better simulate the water holding capacities in the 0 to 50 cm soil profile, crop water-use for spring wheat in the Canadian prairies was well estimated.

To further assess the suitability of DNDC to simulate crop growth, water balance (ET and soil moisture) and NEE, the model was compared to other process-based biogeochemical models (Table 9).

Table 9 Comparison of DNDC to other process-based geochemical models capable of simulating crop growth, water balance and NEE.

Model		Comparison Comments
DNDC	Denitrification and Decomposition (Li et al. 1992a/b, 1994; Li 2000)	One dimensional soil flows / Daily time step (ISEOS 2012)
APSIM	Agricultural Production Systems Simulator McCown et al. 1996 (Australia)	Comparable outputs – quasi two dimensional soil flows (Huth et al. 2012)
Century	Century Soil Organic Model Parton et al. 1983 (USA)	Monthly time step (NREL 2014)
DayCent	Daily Century Model Parton et al. 1998 (USA)	Comparable outputs – one dimension soil flows (NREL 2014)
EPIC	Environmental Policy Integrated Climate Model Williams et al. 1984 (USA)	Comparable outputs – two dimension soil flows (Taylor 2014)
MEDLI	Model for Effluent Disposal Using Land Irrigation Gardner et al. 1996 (Australia)	C and ph not included (CRC 2012)
PERFECT	Production Erosion Runoff Functions to Evaluate Conservation Techniques Littleboy et al. 1989 (Australia)	Largely incorporated into APSIM (Probert et al 1998)
SOCRATES	Soil Organic Carbon Reserves and Transformations in Agro-Ecosystems Grace and Ladd 1995 (Australia)	Weekly time step (Grace et al. 2006)
SWAT	Soil and Water Assessment Tool Arnold and Allen 1993 (USA)	Comparable outputs – two dimension soil flows (Arnold et al. 2012)

Three models, APSIM - Agricultural Production Systems Simulator (McCown et al. 1996), SWAT- Soil and Water Assessment Tool (Arnold and Allen 1992) and EPIC - Environmental Policy Integrated Climate Model (Williams et al. 1984), were considered as potentially useful alternatives to DNDC with the others being excluded for reasons which included incorrect time step and the requirement of multiple models (Table 9). Although the four models have various technical differences and similarities, all were found capable of providing essentially the same output parameters for soil, crop growth, nutrient (carbon, nitrogen and phosphorus) and water cycling (Arnold et al. 2012, ISEOS

2012; Holzworth et al. 2014, Taylor 2014). The only noted exception was the inability of DNDC to simulate lateral soil water flow. The absence of the two-dimensional soil flow simulation, however, does not affect calculation of the water balance in WatBal-Dairy, i.e. estimates for water soil storage, leaching and runoff are provided. As an added benefit, DNDC has been previously used by AAFC (Ottawa) and several dairy crop growth algorithms have been calibrated to Canadian conditions. This is important as linking agricultural activities with the local environmental circumstances is the main obstacle to using process-based models (Lui et al. 2006; Mulligan (2006) as cited in Liep et al. 2007).

3. Methods

3.1. Site Description

3.1.1. Alfalfa Fields

Four alfalfa fields (2 first year growth, 2 second year growth) located in and around the National Capital Region served as experimental sites during this study (Figure 1 and Table 10). Site A1, the Canadian Food Inspection Agency (CFIA) site located in southwest Ottawa, was the primary experimental location with intensive instrumental and manual measurements providing data to: (a) enable simulation of alfalfa growth with the existing DNDC model; (b) facilitate validation of the DNDC alfalfa growth curve, ET, NEE and soil moisture simulations, and; (c) assist with the future calibration of alfalfa algorithms in Can-DNDC by AAFC personnel. Site A2 to A4 were selected for this study due to a pre-existing relationship between the producers and AAFC. Extensive manual sampling of biomass and soil characteristics were undertaken at Sites A2 to A4 to support DNDC growth curve validation.

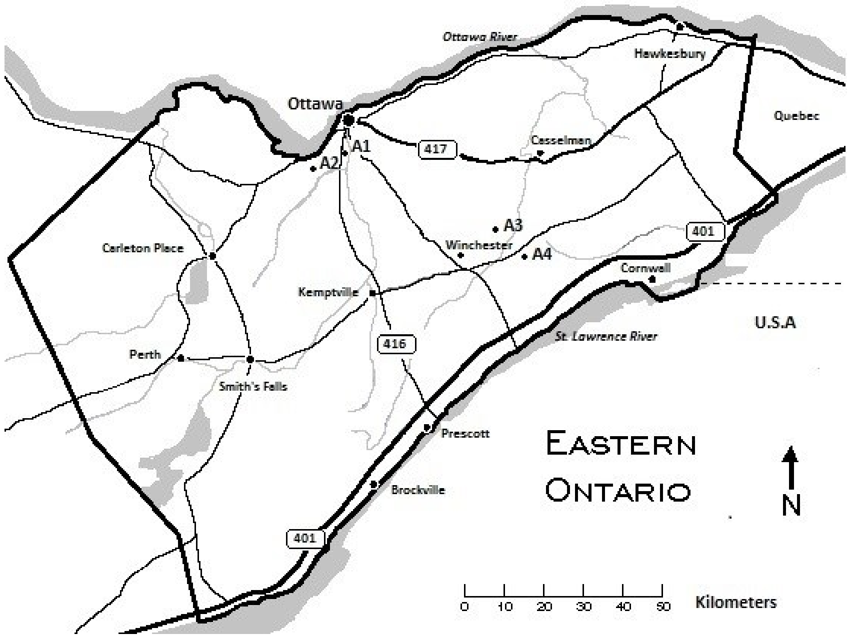

Figure 1 Locations of alfalfa study sites (A1-A4) in the National Capital Region of Eastern Ontario.

Table 10 Description of alfalfa study sites.

SITE	LOCATION	GPS COORDINATES	CROP DESCRIPTION	OTHER DESCRIPTORS
A1	Canadian Food Inspection Agency (CFIA) experimental field – South West Ottawa	45°17′57.10”N, 75°46′05.06″W	First year alfalfa	Wheat in 2013 Sandy loam soil
A2	Private Robotic farm- Fallowfield, Ontario	45°15′06.17”N, 75°49′46.13″W	Second year alfalfa	Corn in 2012 Sandy loam soil
A3	Private tie-stall farm- Morewood, Ontario	45°10′23.14”N, 75°16′02.08″W	First year 70% / 30% alfalfa/timothy grass	Soybean in 2013 Sandy loam soil
A4	Private tie-stall farm- Chesterville, Ontario	45°05′49.90”N, 75°10′55.99″W	Second year 80% / 20% alfalfa/orchard grass	Corn in 2012 Sandy loam soil

3.1.2. Dairy Farm Site (Cattle, Barn, Pasture)

The farm study site used to monitor in-barn, pasture and animal water-use is located in Morewood, Ontario, and includes alfalfa site A3. The farm is a family-operated tie-stall dairy operation with just over 300 acres (121.4 ha) of rain-fed cultivated and pastured land. All of the crops produced on the farm were used on site with the exception of 20.2 ha of corn and 8.1 ha of soybean. Crops are generally rotated on an annual basis (Table 11). In addition to manure and chemical fertilizer use, Embutox, a post-emergent herbicide, was applied to the primary alfalfa/grass field in June at a rate of 30 L ha^{-1}. The farmer used conventional tilling practices on annual crop fields with the exception of the spring wheat field where no till management was used. Perennial hay (alfalfa/grass) and pasture fields were also not tilled.

Grazing is employed from mid-May to mid-October. All non-milk producing cows 17 months and older (dry cows and bred heifers) are put to pasture throughout this period resulting in seasonal changes in diet (Table 12). The pasture is comprised of mixed grasses with treed-bush and has adequate shade for all animals. Drinking water originates from a creek and is provided to the cattle using two small troughs which fill via nose-pumps. Cattle cannot directly access the creek.

Lactating cows have unlimited access to a grassed-yard, approximately 4 ha in size, adjacent to the milking barn during the mid-May to mid-October period; yard water is provided in a trough. In general, the high moisture corn and soybean meals that supplement lactating cow grass and hay intake during the warmer period are fed in the barn at milking while, in the late fall to early spring period, the three servings are given at 04:30 h 10:30 h and 15:30 h (Table 12).

Table 11 Descriptors of feed crops and forage grown and used at the Morewood, Ontario, study farm (A3) for 2014.

CROP	HECTARES/ SOIL	TILE DRAINAGE	CHEMICAL FERTILIZER	PLANT DATE (mm/dd)	HARVEST DATE (mm/dd)	HARVESTED MOISTURE CONTENT
Corn	14.4 / clay loam	40' centres	Manure (BC)* 180 lb of 9-27-16 at seeding (SD)*	04/ 28	10/ 03 silage 10/10 HMC *	55% Silage 26% HMC
Alfalfa/grass (70/30)	6.5 / sandy loam	60' centres	280 lb of 8-19-26 (BC)	04/25	07/02, 08/06, 09/08	35%
Hay (alfalfa/grass)	26.3 / loam	Limited	150 lb of 40-0-0 (BC)	N/A	2-4 CUTS	
Soybean	12.1 / sandy loam	50' centres	150 lb of 4-20-34 (SD)	05/11	10/07	13%
Spring wheat (hard red)	14.1 / sandy loam	50' centres ~ 3 hectares	300 lb of 27-14-8 (BC)	04/ 25	08/05	14% baled as bedding straw
Pasture (grass blend)	21.0 / clay loam	None	N/A	N/A	N/A	N/A
CASH CROPS						
Corn	12.1/ sandy loam	60' centres	200 lb (BC) 180 lb of 9-26-16 at seeding (SD)	05/08	11/18	21%
Corn	8.1/ sandy loam	50' centres	Manure (2 ha) (BC) 200 lb (BC) + 180 lb of 9-26-16 at seeding (SD)	05/08	11/18	21%
Soybean	8.1/ sandy loam	50' centres	No till /no fertilizer	05/20	11/03	13.6%

*(BC) BROADCAST; (SD) SIDE-DRESSED; HMC HIGH MOISTURE CORN

Table 12 Cattle diets by life stage including pasture at the Morewood, Ontario studay farm (A3) for 2014.

LIFE STAGE	MID-OCTOBER TO MID-MAY	MID-MAY TO MID-OCTOBER
Lactating cows	• 24 hour access to free choice balage (25% protein, 35% moisture) • HMC* ~ 20 lb d^{-1} cow^{-1} in 3 servings (12% protein, 26% moisture) • Corn silage ~ 15 lb d^{-1} cow^{-1} in 2 servings (55% moisture) • Soybeans lb d^{-1} cow^{-1} in 3 servings	• Free choice pasture • Free choice balage • HMC ~ 12 lb d^{-1} cow^{-1} in 2 servings • Soybeans ~ 3 lb d^{-1} cow^{-1} in 2 servings • Free choice salt and mineral block
Dry cows and heifers (17 – 24 months)	• Free choice of dry grass hay (1st or 2nd cut) • HMC ~ 3 lb d^{-1} cow^{-1} • Corn silage ~ 30 lb d^{-1} cow^{-1} • Soybeans ~ 1.5 lb d^{-1} cow^{-1}	• Free choice pasture with varying amounts of free choice dry grass hay • Free choice salt and mineral block
Heifers (2 - 17 months)	• Free choice dry grass hay • HMC ~ 2 lb d^{-1} cow^{-1} • Free choice corn silage • Soybeans ~ 1 lb d^{-1} cow^{-1} • ~10% of feed is calf starter (2 – 6 months)	• No pasture • Free choice dry grass hay • HMC ~ 2 lb d^{-1} cow^{-1} • Soybeans ~ 1 lb d^{-1} cow^{-1} • Free choice salt and mineral block (6+ mo)
Calves (0 -60 days)	• 4 litres of milk in 2 servings • ~ 6 lb maximum of calf starter (always available / intake increases with age)	• 4 litres of milk in 2 servings • ~ 6 lb maximum of calf starter (always available/ intake increases with age)

*HMC High Moisture Corn

On average, there are 78 Holstein cows on the farm with only a slight variation in this number throughout the year as a result of fluctuations in calving and culling. The animal population is generally broken down as: 38 lactating cows, 7 dry cows, 5 heifers (2 to 6 months), 11 heifers (6 to 15 months), 13 heifers (15 to 24 months) and 4 calves 0 to 60 days old. In 2014, there were 18 cows culled for performance and health reasons, and 7 animals sold (2 calves and 5 heifers) to other farms as replacement animals. Bull calves are not included in the animal population as they are only kept on the farm for 2 to 3 days.

Lactating cows are housed in the tie-stall dairy barn. The stalls are face-to-face with a feeding alley between the two rows (Figure 2 and 3). Cows have free access to water by means of individual drinking bowls that are automatically replenished, as required. Calves are housed in a separate nursery section within the barn until 2 months old then moved to a second barn until they are approximately 17 months. At this time, they may be put to pasture depending on the time of year. The milking barn is cooled through a Secco International tunnel ventilation system (St. Hyacinthe, QC), and has three bucket fans; no water is required for operation of the ventilation system or fans.

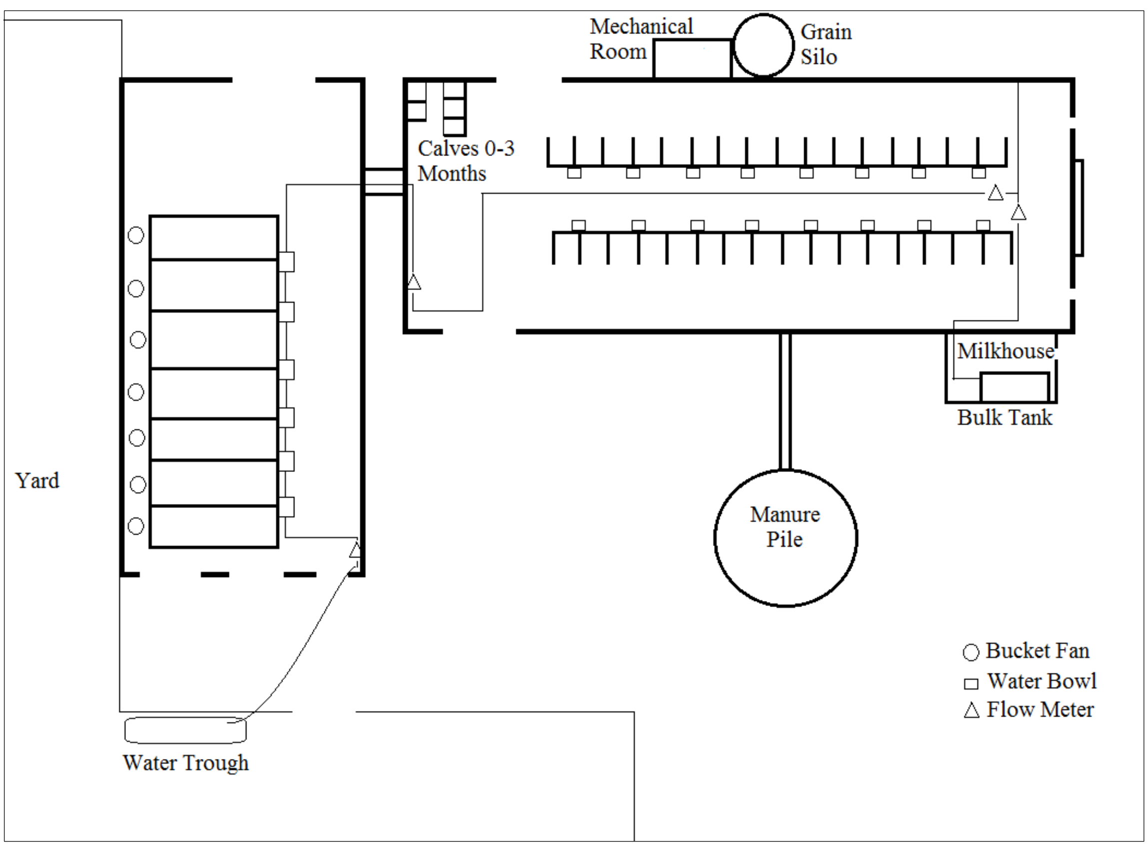

Figure 2 Schematic of study barn located at Morewood, Ontario (A3) with locations of four flow meters and major water pipelines.

Figure 3 Tie stall operation at Morewood, Ontario (A3) study site.

A second free-stall barn, connected to the back of the dairy barn, houses dry cows and heifers. This barn offers free access to water through multiple communal water bowls. There is no cooling system in the barn as it receives limited use in the summer due to pasturing practices. A series of smaller bucket fans provide ventilation to the barn when required. Animal bedding for both barns is primarily spring wheat straw that is grown on-site; wood shavings are used to supplement straw, as required. It is estimated that approximately 1500 lb of straw are used each week. All drinking water used in the barns comes from a deep well which is tested annually.

Dairy cows are milked twice daily throughout the year at 4:00 am and 4:00 pm. In 2014, the average daily production was 28.4 L cow^{-1} with a fat content of 4.1% and a protein content of 3.2%. Water requirements in the actual milking process are minimal with less than 5 L d^{-1} being used for udder cleaning. The farm uses DeLaval

(Peterborough, ON) milking equipment comprised of a stanchion system with pipelines situated above the cattle's head, and a compressor refrigeration system that pre-cools and maintains the temperature of the milk in the bulk tank. Milk is tested and transported from the farm every second day.

Water used for cleaning milking equipment also originates from the deep well. Sanitizing, rinsing, detergent washing and acid rinsing of the milk pipelines is conducted after each milking and the milkhouse is cleaned daily. The bulk tank is cleaned routinely after milk is removed for transport. Water is not used for cleaning housing areas and troughs and drinking bowls require cleansing only once or twice per season.

Solid waste is scraped twice daily from both barns and transported via a conveyor belt system (milking barn) or manually (back barn) to an uncovered manure pile behind the milking barn. The farm employs a solid manure system in which milkhouse washwater is drained directly into a septic system consisting of two tanks with 400 feet of weeping tile and a total 850 gallon (3,217 L) capacity. Tanks are pumped twice annually by a broker and waste removed from the farm site for storage or off-site nutrient application as stipulated in the Ontario *Nutrient Management Act, 2002*.

3.2. Instrumentation and Sampling

3.2.1. Alfalfa Field Measurements

To accommodate the identification of shortcomings in the existing DNDC growth algorithm, *in situ* measurements of ET, NEE, biomass, and soil moisture were collected from Site A1 during the 2014 growing season. Soil sampling and climatic variables were also conducted at Site A1 to populate the mandatory and field specific modeling parameters noted in Table 13. Additionally, manual biomass, soil moisture measurements and soil sampling were collected from sites A2, A3 and A4 during the 2014 growing season. The data was provided to AAFC modellers to assist in calibrating and validating the alfalfa growth algorithm and biomass partitioning in DNDC.

3.2.1.1. Climate data

Historical climate data was entered into DNDC for the ten year period prior to the study year based on data obtained from an AAFC weather station located adjacent to Site A1. Climate data for the 2014 study year relating to temperature, humidity and wind speed were collected from a closed-path eddy covariance (CPEC) system installed at Site A1. Readings, taken at a frequency of 10Hz, were averaged to provide daily values for entry into the DNDC model. Details relating to the CPEC system are found in Section 3.2.1.6**.** Precipitation and radiation data for 2014 were obtained from the on-site AAFC weather station.

Table 13 Mandatory and site specific parameters required for DNDC crop simulations with methods used to collect the data.

DNDC SUB-MODEL	DNDC PARAMETER	DATA COLLECTION METHOD
Climate	Day of year	Historical records 2003-2013 / CPEC 2014
	Minimum temperature	Historical records 2003-2013 / CPEC 2014
	Maximum temperature	Historical records 2003-2013 / CPEC 2014
	Precipitation	Historical records 2003-2013 / CPEC 2014
	Wind speed	Historical records 2003-2013 / CPEC 2014
	Humidity	Historical records 2003-2013 / CPEC 2014
	Radiation	Historical records 2003-2013 / CPEC 2014
Soil	Texture	*In situ* measurement
	Bulk density	*In situ* measurement
	pH	*In situ* measurement
	Clay fraction	*In situ* measurement
	Field capacity	Hydraulic properties calculator (Saxton and Rawls 2009)
	Wilting point	Hydraulic properties calculator (Saxton and Rawls 2009)
	Hydraulic-conductivity	Hydraulic properties calculator (Saxton and Rawls 2009)
	Porosity	Hydraulic properties calculator (Saxton and Rawls 2009)
Cropping	Field cropping history (rotation)	Historical records 2003-2013 / farmer consultation
Crop	Type of crop	Personal observation / farmer consultation
	Planting and harvesting dates	Personal observation / farmer consultation
	Biomass	*In situ* measurement / AAFC consultation
Tillage	Date of tillage	Personal observation / farmer consultation
	Tilling method	Personal observation / farmer consultation

3.2.1.2. Soil characteristics

Soil texture, clay fraction and pH were obtained from soil samples collected from Sites A1 to A4 on June 4, August 7 and September 24, 2014. A hand-held sampling probe (Oakfield Apparatus Company, Oakfield, WI, USA) was inserted into the soil to a depth of 0.20 m at four random locations. The core was collected, placed in a bucket and blended to create a composite sample. The sample was bagged, labelled and transferred to the AAFC lab for analysis. Texture and clay fraction were determined through an analysis of particle size using the Hydrometer Method modified from Tan (1996). Soil pH was determined using 1:1 ratio soil/water slurry composed of a 10 g of soil and 10 ml of de-ionized water. The slurry was loaded into a falcon tube and agitated in an orbital shaker for 10 minutes. A calibrated pH electrode meter (IQ150W ISFET Probe, Spectrum Technologies, Inc., Plainfield, IL) was then used to determine pH.

Bulk density was ascertained from soil samples collected for gravimetric soil moisture content; details are noted in Section 3.2.1.3. After oven drying, bulk density was determined by dividing the dry weight of cored samples with the corer volume (130 cm^3). Field capacity, wilting point, hydraulic conductivity (by matric potential) and porosity were calculated with the USDA/Washington State Hydraulic Properties Calculator (Saxton and Rawls, 2009) based on sand and clay fractions determined during texture analysis.

3.2.1.3. Soil moisture and temperature measurements

Volumetric water content of soil was assessed at each of the study sites at the mid-point and end of the growing season. For each assessment, a trench providing access to a flat, accessible vertical surface was dug to a depth exceeding 50 cm. A hand held 12 cm time-domain reflectometer (TDR) soil moisture meter (Field Scout TDR 100 Moisture Meter (Spectrum Technologies, Inc., Plainsfield, IL)) was inserted horizontally into the soil wall at depths of 5, 10, 20, 30 and 50 cm and volumetric water content recorded. Vertical TDR 100 probe readings of soil moisture at 5cm were also collected from the study sites at the time of biomass sampling (every 7-10 d). Four temperatures were taken in proximity to the biomass sampling areas and results averaged.

Volumetric water content was also determined manually and used to validate the horizontal TDR 100 measurements. Metal cores with a volume of 130 cm^3 were hammered horizontally into the soil adjacent to the TDR 100 testing sites. Cores were removed, bagged by depth, labelled with date and depth of collection and taken to the AAFC lab where they were weighed. Samples were then dried at 110 ^oC in a forced-air oven for 48 hours and re-weighed. Moisture content was determined for each depth by subtracting dry weight from wet weight. Gravimetric moisture (kg kg^{-1}) was converted to volumetric water content (m^3 m^{-3}) by multiplying by sample bulk density (kg soil m^{-3} soil) and dividing by water density (kg water m^{-3} water). A strong correlation was noted between the horizontal TDR 100 and manual measurements ($r = 0.83$) as noted in Appendix A.

Four CS616 Water Content Reflectometers (Campbell Scientific, Logan UT) were also installed to provide continuous readings of average soil volumetric water content at Site A-1 from June 19 to November 11, 2014. A CS616 two-pronged sensor was placed horizontally into the face of a soil pit at 50, 20, 10 and 5 cm depths below the surface (Figure 3). Data was recorded at 5-min intervals using a CR3000 datalogger (Campbell Scientific, Logan, UT).

To enable continuous measurements of soil heat flux, heat capacity and the rate of change in storage of energy in the surface soil, heat flux plates and thermocouples (Campbell Scientific, Logan, UT) were installed in conjunction with the CS616 Reflectometers (Figure 4). Two HFT3 Soil Heat Flux Plates were installed at approximately 40 cm from either side of the upper CS616 sensors. The soil was carefully split and a HFT3 was inserted into the undisturbed soil profile at a depth of 8 cm. The soil was replaced ensuring contact with the sensor. A pair of TCAV-E Averaging Thermocouple probes was installed in the immediate area of both HFT3 Plates at a depth of 5 cm approximately 5 cm apart. Three TCAV-T single wire temperature probes were installed in close proximity to the CS616 sensors at depths of 10, 20 and 50 cm. All sensors were recorded on the CR3000 datalogger every 5-min. More instrument details are included in Appendix B.

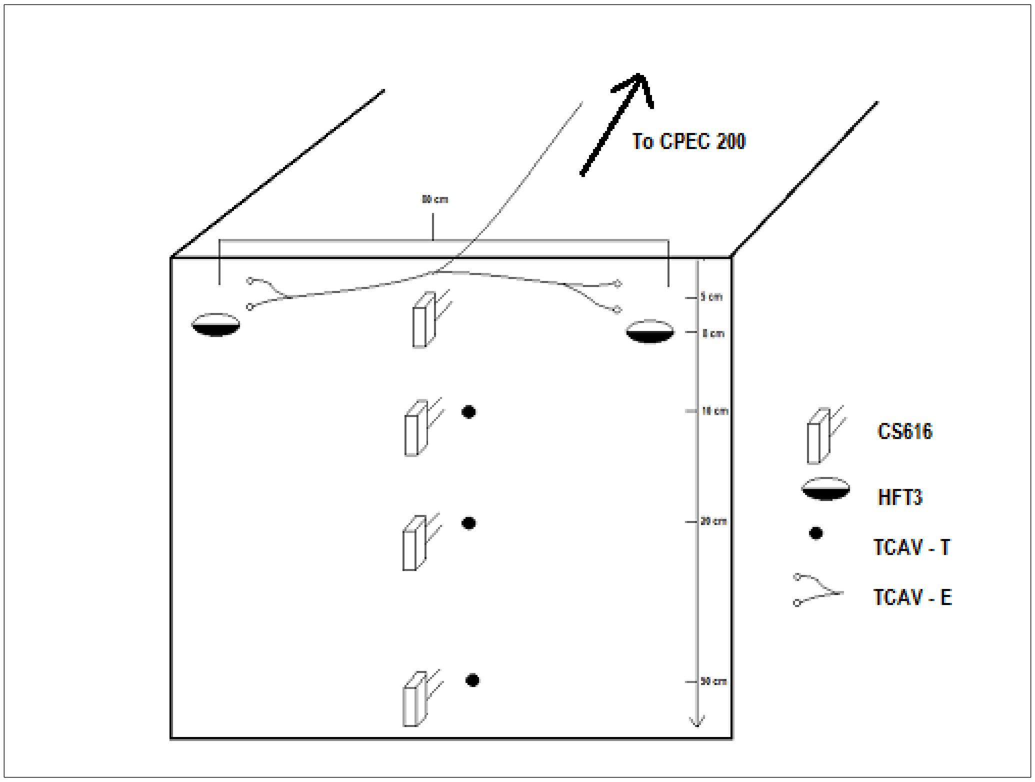

Figure 4 Set-up of supplemental sensors installed at site A1 to collect soil moisture, soil heat flux, and soil temperature data in support of proposed AAFC calibration of DNDC-CAN.

3.2.1.4. Crop and cropping parameters

Field cropping parameters for the 2003 to 2013 period relevant to Site A1 were loaded into the DNDC system based on records provided by the AAFC field manager. Details relating to the 2014 crop and management methods were based on first-hand observation.

3.2.1.5. Biomass measurements

Biomass sampling occurred on a near weekly basis (every 7-10 d) from June 10 to November 6, 2014, at all field sites. During collection, a 0.25 m^2 quadrant frame was randomly placed in four locations within each field to make a composite 1 m^2 sample

Figure 5). All plants within the frame were cut down to soil level, separated into groupings of alfalfa, grass and other plant materials, bagged and labeled. Samples were immediately returned to the AAFC lab where like-materials from the four samples were combined, weighed for wet biomass weight, and then dried at 70 ^{o}C in a forced-air oven for 48 hours. Samples were re-weighed and the above ground biomass was calculated on kg DM ha^{-1}. Results were used to determine the growth curve for each alfalfa site for comparison to the DNDC estimated growth curve.

Figure 5 Alfalfa biomass sampling quadrat frame used at study sites A1 to A4 during 2014 growing season.

3.2.1.6. ET and NEE measurements

A Campbell Scientific (Logan, UT) closed path eddy covariance system (CPEC200) comprised of closed-path CO_2/H_2O gas analyzer (model EC155), a sonic anemometer (model CSAT3A), and a datalogger (model CR3000) with a cellular modem (CS 2013) was installed in a central location at Site A1 (Figure 6). The CPEC200 was located on a tripod 2 m above the vegetation canopy from June 7 to November 6, 2014 (DOY 158 to 310) and provided measurements at 30-min intervals for CO_2 and H_2O fluxes, heat flux and momentum, soil temperature and moisture, three dimensional wind speed (model CSAT3), and air temperature. To assist with the proposed calibration of the DNDC-Can alfalfa algorithms, net radiation was measured with a NR-LITE Net Radiometer (Campbell Scientific, Logan, UT). Data was recorded at a frequency of 10 Hz by the CR3000 datalogger then downloaded via Loggernet Software from a Compact Flash memory card for processing. EddyPro (Version 5.2.1) (LI-COR Biosciences Inc., Lincoln, NE) was used to process raw flux data from the CPEC200 system with selected processing options listed in Appendix C. Computed 30-min results were retained for further analysis when the CO_2 and H_2O flux footprints (Kljun et al. 2004) were within the boundaries of the field. The data was also quality controlled through various system signals including limits in 30-min standard deviations (σ) of sonic temperature ($\sigma<2\ ^oC$), IRGA temperature ($\sigma<1\ ^oC$), pressure ($\sigma<0.5$ kPa), H_2O ($\sigma<5$ mmol mol^{-1}) and CO_2 ($\sigma<20$ µmol mol^{-1}) and rotated vertical wind speed (mean = 0, $\sigma>0.075$ m s^{-1}). This resulted in 58.5 % of the flux data being rejected with 12 d being the longest data gap as a result of technical difficulties with the CPEC200. Matlab software (version 7.12.0.635(R2011a), The MathWorks, Inc., Natick, MA) was used to fill gaps in the data (gap filling) to create a complete data set for latent heat flux (converted to ET) and CO_2 flux (converted to NEE). In the gap filling process, data was initially separated into daytime and nighttime fluxes and then broken up into blocks of time based on the growth phase of the crop, generally about 20-d long. Small gaps (8 or less consecutive 30-min periods) in the data sets were then filled by linear interpolation. Larger gaps were filled using basic regression models. For daytime CO_2 fluxes, a second order polynomial was used with photosynthetically active photon flux density while air and soil temperature were used for nighttime fluxes. For daytime latent heat flux, photosynthetically active photon flux density and vapour pressure deficit were used for regression modeling. Nighttime latent heat gaps were filled with models based on temperature, vapor pressure deficit and wind speed. For multi day gaps, the same basic linear regression model parameters were used; however, they were applied on a daily time step using daily average photosynthetically active photon flux density and temperature.

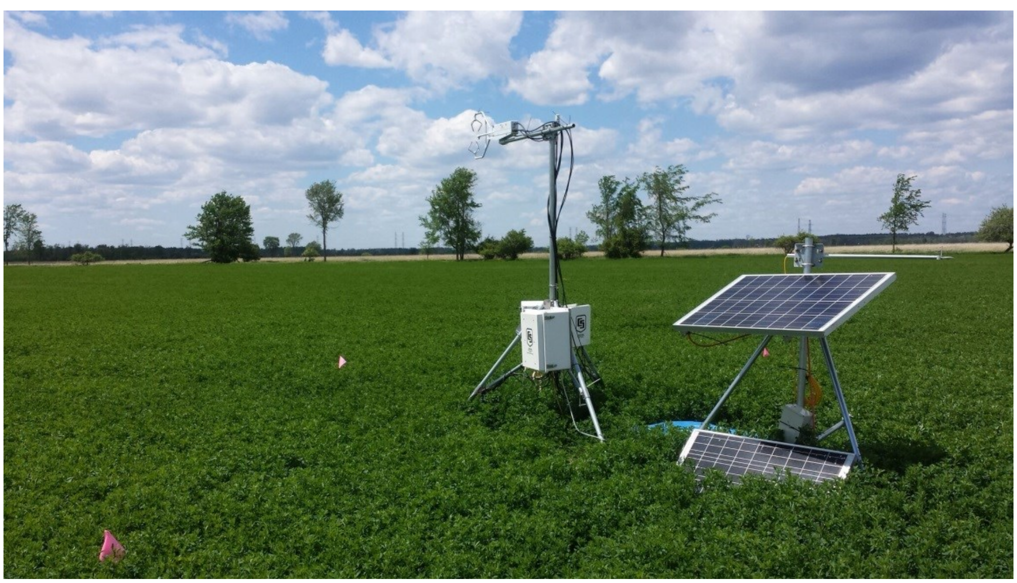

Figure 6 Campbell Scientific closed path eddy covariance system comprised of closed-path CO2/H2O gas analyzer, a sonic anemometer, and a datalogger with cellular modem installed at study site A1 during 2014 growing season.

3.2.2. Cattle, Barn and Pasture Measurements

3.2.2.1. Measurements for cattle free water intake

Flow meters (Carlon Meter, Grand Haven, MI) were installed in early fall 2014 to monitor water flow to the barn and yard environments (Figure 7). Two Model 1000JLPRS meters, with USB data storage, outputting a pulse for every 0.5 L of water flow and a Model 625JLPRS meter (0.25 L $pulse^{-1}$) were installed along a common line servicing the main and back barns (Figure 2). The placement of the meters permitted the calculation of drinking water for lactating cows and calves in the milking barn, non-lactating (dry cows and heifers) cattle in the back barn and lactating cows in the yard. Based on farmer input on animal numbers, estimations of daily animal FWI were made.

Figure 7 Two Carlon flow meters, Model 1000JLPRS with USB storage, installed to monitor water flow in barn environment at Morewood, Ontario (A3) study site.

3.2.2.2. Measurements for barn cleaning water-use

A Model 1000JLPRS meter (0.5 L pulse^{-1}) was also installed along an independent line leading to the milkhouse (Figure 2). The meter permitted exclusive quantification of washwater; specifically, the water used to clean the milk pipelines, the milkhouse and the bulk tank.

3.2.2.3. Measurements for cattle water intake in pasture

To assess the FWI of dry cows and bred heifers in the pasture, flow meters (model FTB8007-PT, Omega Engineering, Inc., Stamford, CT) were installed on two nose pumps from mid-September to early November 2014. Meters provided pulse measurements of water-use at 20 pulses to 1 US gallon of water. Data was recorded by USB dataloggers housed within each meter. Water-use per animal was determined based on farmer-supplied data for the number of grazing animals and the time of grazing.

3.2.2.4. Recording farm practices

A farmer-input questionnaire (Appendix D) was designed based on research and consultation with the dairy producer and AAFC personnel to facilitate the collection of data required for analysis and identification of the equations used in the WatBal-Dairy prototype and/or for testing of the calculator. The producer provided farm-specific details that related to crops and crop management, milk management, manure management, cooling systems, cattle numbers by life stage, milk production and feed including details of diet composition and quantity, moisture content and crude protein for non-pasture inputs.

3.3. Water-Use Framework Development, Testing, Calculations and Statistical Analysis

3.3.1. Wat-Bal Dairy Framework Development and Testing

The WatBal-Dairy prototype was developed to facilitate quantification and analysis of field-to farm-gate water-use. The initial criteria for development of the framework, including potential water inputs, outputs and storage in the field, cattle, barn and pasture environments, were identified through a detailed review of literature and a series of consultations with AAFC personnel and dairy farmers (Appendix E 1-3). A scoping process established study boundaries, limitations, exemptions and assumptions which led to the identification of final quantification parameters (Appendix F and G).

The prototype framework was developed as an Excel Workbook consisting of 9 tabs (Box 1). Inputs into Tab 2 relate to crops (including pasture), field management practices, diet and water inputs for cattle with pasture and yard access. Tab 3 inputs pertain to diet and water inputs for confined cattle and non-drinking (milkhouse and cleaning) water-use. Tab 4 provides a summary of water-use and balance results by environment, crop type, cattle life-stage and the full-farm system. The equations, calculations and results supporting Tab 4 entries are found by environment in Tabs 5-8. Tab 9 has been included to demonstrate the applicability of WatBal-Dairy results to existing footprinting methodologies.

Tab 1 – Introduction with Instructions

Tab 2 – User Inputs for Field and Pasture (Field and Cattle)

Tab 3 – User Inputs for Housed Cattle and Barn

Tab 4 – Calculation Results

Tab 5 – Field Environment Calculations

Tab 6 – Animal Environment Calculations

Tab 7 – Pasture Environment Calculations

Tab 8 – Barn Environment Calculations

Tab 9 – Example Application of Results to the WFN Water Footprint

Box 1 Basic structure of WatBal-Dairy Excel spreadsheet.

Water-use calculations in the prototype are based on balance equations that were developed to reflect water flows within and between the four farm environments. To accommodate the calculation of the full-farm water-use, outputs in each environment are identified as either consumed (water that is being removed from the farm environment) or non-consumed (water recycled within the farm environment).

In the field environment, water-use (ET) is determined through a modified version of eqn 3. In the equation (eqn 33), capillary rise is assumed negligible (Li et al. 2008; Djaman and Irmak 2013), and water contained in the crops is included as a non-consumed output. While the quantity of water in plants is minimal, inclusion in the equation is needed for calculations of water flows at the farm-system level.

Water Balance for Field Environment

$$(33) \qquad P + I + AW = (ET + PW^{*} + DP + R) + \Delta S$$

where P is precipitation (kg), I is irrigation (kg), AW is added water including water in manure or mixed with pesticides, insecticides and fungicides, ET is evapotranspiration (kg), PW is water stored in the plant, DP is deep percolation (kg), R is runoff (kg), and ΔS is change in soil moisture (kg).
* PW = non-consumed output

In the cattle environment, eqn 34 is used. The equation assumes that water retained in the animal is the point of storage and is equivalent to 0. Total body water accounts for 56 to 81% of cattle body weight (Beede 1991), and fluctuates throughout the life of dairy cattle based on age, health and stage of lactation (NRC-USA 2001). On a daily basis, however, the change in body water weight is negligible. Silanikove et al. (1997) noted that a milk-free water balance for all cattle warranted an assumption of a steady-state storage condition while Boudon et al. (2012) also showed that an increase in evaporative loss associated with thermoregulation was totally compensated for by FWI, indicating no change in body water due to increased temperature. With the 0 storage assumption, inputs equal outputs and actual water-use is determined through the quantity of water consumed in milk and respiratory cutaneous water loss.

Water Balance for the Cattle Environment

(34) $\Delta S = FWI + RWI + MetW - (MW + RCW) - (FW + UW)^*$

where ΔS is the change in body water (kg) (assumed to equal 0), FWI is free water intake (kg), RWI is ration water intake (kg), MetW is metabolic water (kg) (Assumed negligible), MW is the water content of milk (MY X 0.87) (kg), RCW is respiratory cutaneous water loss (kg), FW is the fecal water content (kg), and UW is the urinary water content (kg)
*(FW + UW) = manure = non-consumed output)

In the barn environment, two equations (eqn 35 and 36) are employed to account for differences between solid waste and semi-solid/liquid manure management systems. Both equations assume 0 storage in the barn environment. Fecal and urine water are calculated in the cattle environment and are not included in barn equations to avoid double accounting. It is assumed, however, that specific barn waste and manure will be combined prior to recycling to the field environment. Eqn 35 applies to a solid manure waste system and assumes that water-use, as represented by the storage factor, is restricted to non-recycled washwater from pipeline and bulk tank cleaning, animal and milk cooling water, and miscellaneous water uses such as milk house cleaning, spilt milk, feed preparation and washroom facilities. Eqn 36 applies to a semi-liquid/liquid manure management system and assumes that all water, with the exception of animal cooling water, is returned to the system via manure, recycled-bedding materials or energy (biogas) inputs. Of note, the percentage of added or lost water in open manure (waste) piles or uncovered slurry tanks has not been considered in WatBal-Dairy calculations.

Water Balance for a Solid Manure Management System

(35) $\Delta S = WW + MCW + CW + BedW + MISC – BedWm^*$

where ΔS is assumed to equal water use = WW is washwater (pipelines and bulk tank) (kg), MCW is water used to cool milk (kg), CW is water used for animal cooling (kg), BedW is the water in bedding material (kg), MISC is miscellaneous water use (kg), FWm is the fecal water content in manure sent to the field (kg), UWm is the urinary water content in manure sent to the field (kg), BedWm is the bedding content in manure sent to the field (kg).
* BedWm = non-consumed outputs

Water Balance for a Semi-Solid / Liquid Manure Management System

(36) $\Delta S = WW + MCW + CW + BedW + MISC - (WWm + MCWm + BedWm + MISCm) + BedWd^*$

where ΔS is assumed to be equal water use = WW is washwater (pipelines, bulk tank, parlour) (kg), MCW is water used to cool milk (kg), CW is water used for animal and milk cooling (kg), BedW is the water in bedding material (kg), MISC is miscellaneous water use (kg), WWm is the washwater in manure (kg), MCWm is the milk cooling water in manure (kg), MISCm is the miscellaneous water in manure (kg), BedWd is the water in dried bedding used in bedding/energy (kg).
(WWm + MCWm + BedWm + MISCm) + BedWd = non-consumed outputs

The full-farm water balance is determined by summing the inputs, outputs and change in storage for each of the four environments (Eqn 37). The calculation of integrated field to farm-gate water-use is reflected by the consumed outputs leaving the farm environment (eqn 38). The extent of the actual use will be contingent on the nature of the farm milking and waste management systems.

Water Balance for Integrated Field to Farm-Gate Operations

$$\text{Inputs } (f+p+c+b) = \text{Outputs } (f+p+c+b) + \Delta S \ (f+p+c+b) \tag{37}$$

where f is the field environment, p the pasture environment, c the cattle environment, and b the barn environment

$$\Delta S = R + DP + ET_C + ETp + MY + RCWp + RCWc + WWnr + MCWnr + CW + MISCnr \tag{38}$$

where ΔS is the total farm-system water use (kg), R is runoff (kg), DP is deep percolation (leaching) (kg), ET_C is crop evapotranspiration from the field (kg), ET_P is crop evapotranspiration from the pasture (kg), MY is water contained in milk (kg), RCW_P is respiratory cutaneous water loss from cows at pasture (kg), RCWc is respiratory cutaneous water loss from cows in confinement (kg), WWnr is non-recycled washwater (milklines, bulk tank, parlour) (kg), MCW is non-recycled water used to cool milk (kg), CW is water used to cool animals (kg), and MISCnr is non-recycled miscellaneous water used in the barn (kg)

Testing of the framework prototype was undertaken using a variety of measured and estimated data (Appendix H) with the farm study site (A3) providing the model, i.e. field and pasture environment size, crop selection, cattle numbers, diet. Measured data for feed quantities and milk output from the thermoneutral period were used to represent an annual time-step with calculations and results reported on a kg day^{-1} basis. For calculation purposes, units were converted as: 1 L water or milk equaled 1 kg (Bishop 2013), and; 1 mm precipitation or ET equaled 1 kg water m^{-2} (McMahon et al. 2013). In reporting results in WatBal-Dairy, units were rounded to the nearest kg.

3.3.2. Field and Pasture Water-Use Calculations in WatBal-Dairy

Crop yield values used in WatBal-Dairy field and pasture environment calculations are noted in the Table 14. As-harvested yield values for corn crops and soybean were based on farmer inputs and closely reflected 2014 average yields (OMAFRA 2015a). The as-harvested alfalfa yield value was calculated from measured dry matter adjusted downward by 15% to reflect the estimated difference in biomass yield between manual collection techniques and mechanical harvesting, i.e. the difference in field residue. The dry spring wheat straw yield was provided by the farmer based on a 14% MC. Pasture yields were based on Ontario estimates for red clover, alfalfa, timothy and orchard grass mixed fields (Kyle 2015). Moisture levels for all field crops were provided by the producer or estimated from existing literature, when necessary. The adjusted as-fed yields for all crops, which reflect the decrease in moisture content from the harvested value, were determined through eqn 39 (Hellevang 1995). Dry matter yields, with the exception of spring wheat, were calculated based on eqn 40. All as-fed values satisfy cattle dietary requirements as provided by the farmer.

Table 14 As harvested and as-fed crop yield estimates with the dry matter content of as-fed weight and ET values used in WatBal-Dairy for crops and pasture at the Morewood, Ontario (A3) testing site.

	Corn Silage	High Moisture Corn	Soy	Alfalfa	Wheat (straw)	Pasture
Field Size (ha)	3.2	10.2	12.1	32.8	14.1	21.0
As-harvested Yield (kg ha-[1])	47,623.8[1] (70%)	10,408[1] (28%)	3,240.3[1] (14%)	21,770.5[2] (65%)	7,757.0[3] (35%)	7,952.0[4] (75%)
As-fed Yield (kg ha^{-1})	31,749.2 (55%)	10,126.7 (26%)	3,203.0 (13%)	11,722.6 (35%)	5,862.8 (14%)	7,952.0 (75%)
Dry Matter Content of As-Fed Yield (kg ha^{-1})	14,287.1	7,493.8	2,786.7	7,619.7	5,042.1	1,988.0
ET (mm)	380.8	397.6	359.1	410.9	306.6	362.6

[1] Based on farmer input relevant to field production and feed requirements.
[2] Reflects measured dry matter content adjusted to reflect estimated difference in post-manual (measured) and post-mechanical (farmer) biomass residue
[3] Based on farmer input for dry straw yield
[4] Based on mixed-grass estimated yield (Kyle 2015)

(39) As-Fed Yield (kg) = 100 – As-Harvested Moisture (%) / 100 - As-Fed Moisture (%) x Harvested Quantity

(Hellevang 1995)

(40) DM (kg) = "As-Fed" Yield x (100 – "As-Fed" Moisture Content)/100

In the absence of ET measurements for crops at the farm study site (A3), and with few ET measurements available for Canadian crops, seasonal ET values (Table 14) were estimated as 70% of the growing season precipitation for each crop with the remaining precipitation allotted to soil storage, runoff and leaching. While runoff and leaching are often negated in crop water-use studies (Rana and Katerji 2000; Zhang et al.2002; Katerji et al.2008; Li et al. 2008; Gervais et al. 2012), the 30% value used in this study is considered a realistic estimate; plant available water held in the soil or lost to runoff and leaching may contribute significantly to the water balance depending on field topography, soil holding capacity (texture and structure), organic matter content, soil layering (AAFC/OMAFRA 1997; Brown 2009; AARD 2013) and soil management practices (McConkey et al. 2011; Osman 2013). As previously discussed, DNDC model results reported by Verge et al. (2015) indicated that leached water exceeded and runoff equalled approximately 50% of the annual accumulated ET in an Eastern Ontario cereal crop. Additionally, in a study of water balance in soybean crops subject to conventional and no till management, soil storage, runoff and deep drainage equaled 37.3% of total inputs under both management practices (Moreira et al. 2015). The ET estimates tend to reflect the influence of crop characteristics on crop water-use as noted in Section 2.4.2. Among the annuals, ET declines relative to plant biomass and the length of the growing season as noted by Allen et al. (1998) and Osman (2013). Additionally, as a perennial, alfalfa has the highest ET value reflecting the extended perennial growing period (Moore 2005; Putman 2010). All of the estimates fell below or close to the low end of published ET ranges including those noted in Table 3. This was not an unexpected result considering that crop water-use is influenced by climate and weather, crop characteristics, soil characteristics and management practices (Allen et al. 1998; Irmak 2009; AARD 2013) and none of the reviewed studies were from the Ontario / Québec area. Of note, the measured ET (213mm) for alfalfa at site A1 suggested that the proposed testing values may actually be too high for the EGLHLE. The Site A3 seasonal alfalfa ET was expected to be higher as the crop was planted a month earlier than Site A1, fertilized, subjected to three as opposed to two cuts and consisted of an alfalfa/timothy blend. Overall, for the purpose of testing WatBal-Dairy, it is believed that partitioning of precipitation into 70% ET and 30% storage, runoff and leaching provided a reasonable representation of water-use at the study site.

Without *in situ* measurements or analysis of manure composition at the time of field application, quantities of manure water returning to the fields were calculated as fresh weights, i.e. equivalent to excrement equation results. Further, for the purpose of analyzing the integrated farm water balance, manure water recycled to the field was assumed to be a blue input based on the heavy influence (80 to 90%) of blue-sourced FWI on manure composition (Beede 2005; Harner et al. 2013). Additionally, although lactating cows spent time in the yard where there was no manure collection, for testing purposes, all manure from lactating cows was assumed to be collected and distributed in the corn fields.

3.3.3. Cattle Water-Use Calculations in WatBal-Dairy

Water inputs and outputs were calculated for both pastured and confined cattle based on thermoneutral life-stage numbers, diet inputs and milk production from the study site (A3). Pasture RWI was based on the USDA-NOP (2011) calculation for dry matter demand minus known supplemental feed inputs (eqn 30a – 30c). Milk production was standardized using the internationally accepted functional unit of 1 kg of fat and protein corrected milk (FPCM) calculated as per eqn 41.

$$\text{(41)} \quad \text{FPCM} = \text{milk yield (kg)} \times (0.337 + 0.116 \times \text{fat content (\%)} + 0.06 \times \text{protein content (\%)})$$

(FAO 2010)

Cattle FWI, non-pasture RWI and output values were estimated with equations embedded into the WatBal-Dairy prototype. Potential equations were identified from the literature noted in Appendix ! and have been previously presented in Chapter 2. Equations used to determine milk water content (eqn 16, Appuhamy et al. 2014) and estimate respiratory cutaneous water loss (eqn 28, Silanikove et al 1995) in WatBal-Dairy are acceptable standards and required no further evaluation.

FWI and DMI equations, the latter of which is required for determination of RWI, were vetted based on their ability to reflect measured thermoneutral and cool period data from the study site, and their practicality of use in the WatBal-Dairy calculator, i.e. the data required to complete equation terms needed to be of reasonable availability considering the potential user pool. Box 2 provides a summary of the equations incorporated into Wat-Bal Dairy. Details of FWI and DMI equation evaluation and the rationale for inclusion in WatBal-Dairy are provided in Appendix J (1).

For FWI, eqn 10 for lactating and dry cows and eqn 7 for all heifer groups were selected as they provided the best results in the thermoneutral period for the noted life-stages, and the best estimation of full-farm FWI relative to actual measurements, i.e. the measured thermoneutral FWI for lactating cows, dry cows and heifers at the study site (A3) was 200.8 kg d^{-1} (plus 9 kg d^{-1} for calves) while the noted equations provided an estimate of 206.3 kg d^{-1}; a difference of 5.5 kg d^{-1} or 2.7%.

As DMI is essential to calculation of FWI, RWI and cattle outputs, eqn 14 and eqn 15 were included in the WatBal-Dairy prototype to enhance the accuracy of calculations. Results from these equations are generated from actual feed intake quantities plus either dry matter or moisture content percentage; information generally known to the farmer. In the event diet information is not available, however, eqn 13 with the most accurate estimate of thermoneutral DMI for lactating cows and eqn 29 with strong estimates for non-lactating cattle were also included in the prototype. In considering all cattle groups, the measured study site DMI was 56.6 and 59.1 kg d^{-1} for the thermoneutral and cool periods respectively. Based on eqn 13 for lactating cows and eqn 29 for other cattle groups, the thermoneutral farm result was under-estimated by 5.4 kg d^{-1} (10.5%) and the cool period 8.6 kg d^{-1} (17%).

In the absence of *in situ* measurements for cattle excretions, the evaluation of identified urine, fecal and manure water equations was based on measurements and estimates taken from the literature noted in Appendix J (2). The identification of accurate excretion estimate values was complicated by variations in outputs due to differences in animal genetics, performance potential of lactating animals, dietary options and farm management (Lorimor et al. 2001; ASAE 2005); it is not uncommon for estimates to vary by as much as 50% (USDA-NRCS 2003). However, to enhance the integrity of the estimates used to assess WatBal-Dairy output equations, identified values were analyzed for trends and evaluated through partitioning of outputs based on the known total water intake and milk water values from the study site (A3). A summary of the estimates and partitioning percentages considered in the review, and the rationale for the selection of the final estimates used in output equation evaluation, is found in Appendix J (3).

Urine, fecal and manure water equations selected for use in WatBal-Dairy are noted in Box 2. Details of the equation evaluation and the selection rationale are found in Appendix J (4). Fecal water eqn 18 and urine eqn 21 were selected for lactating and dry cows based on a favourable comparison of combined results to identified estimated values in both the thermoneutral and cool periods, and credible output partitioning values. The equations also promoted responsiveness, i.e. calculations were not limited to a variable such as the body weight based. Manure water (urine and fecal water) eqn 25 was deemed the best fit for heifers with credible output partitioning results relative to the other potential equations.

	CATTLE GROUP	EQUATION DESCRIPTION	EQUATION
CATTLE INTAKE			
Free Water Intake (FWI)	Lactating / Dry	(10) Adams and Sharpe 1995 (Modified Kertz)	TWI = (4 × DMI) + KG of 4% FCM + 25.6 FWI = TWI – RWI where: 4% FCM = (0.4 × MY + 15 × (MY × FCM AS A DECIMAL) RWI = DMI/DM ×MC
	Heifers	(7) Holter and Urban 1992 (Three Variable)	FWI = -10.34 + (0.23 × DM) + (2.21 × DMI) + (0.039 × CP (% DM)^2 where: DM is dietary dry matter (g) (%); DMI is dry matter intake (kg d^{-1}) and CP is crude protein in DM (%)
Dry Matter Intake (DMI) Primary Equations	All Cattle	(14/15) USDA-NOP 2011 (As-Fed Calculation)	DMI = FT × DM (%) or DMI = FT – RWI where: FT is the quantity of daily feed by type (kg), DM (%) is the percentage of dry matter content of the feed and RWI is ration water intake as per Eqn 15 (RWI = FT × Moisture Content (%))
DMI Secondary Equations	Lactating	(13) McGill University (N.D.)	DMI (% of BW) = 4.048 – 0.00387 × BW + 0.0584 × 4% FCM where: BW is body weight (kg) and 4% FCM is equal to (0.4 × actual milk yield in kg d^{-1}) + (15 × milk fat in kg d-1)
	Non-Lactating	(29) Minson and McDonald 1987	DMI = (1.185 + 0.00454BW – 0.0000026BW2 + 0.315ADG)2 where: BW is body weight (kg) and ADG is average daily gain (kg d^{-1})
CATTLE EXCRETIONS			
Fecal Water (FW)	Lactating / Dry	(18) Holter and Urban 1992	FW = 5.52 + (1.32 × DMI) + (0.038 × DM) where: DMI is dry matter intake and DM is dietary dry matter (g) (%)
Urine (U_E)	Lactating / Dry	(21) Weiss 2004	U_E = 12.3 + (0.72 × DMI) – (0.11 × CS) where: DMI is dry matter intake and CS is the % of corn silage in forage DM
Manure Water (M_E)	Heifers	(25) ASAE 2005	M_E = (DMI × 3.89) – (BW × 0.029) + 5.64 where: DMI is dry matter intake and BW is body weight

Box 2 Cattle input and output equations selected for inclusion in the WatBal-Dairy prototype by cattle group.

3.3.4. *Barn Water-Use Calculations in WatBal-Dairy*

The extent of washwater use, the degree of recycling and the outcome of waste are the major points of consideration relative to barn water usage (i.e. non-drinking water). The Ontario government's Nutrient Management (OMAFRA 2015) software program, a publically available tool which enables estimation of daily washwater volumes, served as the basis for barn water-use calculations in WatBal-Dairy. The Nutrient Management software was originally based on washwater parameters from a study by Cuthbertson et al. (1994) in which 308 Ontario farms were surveyed and washwater recorded based on supplier calculations. In recent years, the program has been updated with equations validated with three years of summer-based measurements (2011-2013) from 29 southern Ontario farms (House et al. 2014). The equations are based on five factors: (1) a mandatory "base use" value reflecting the type of milking system developed from Cuthbertson et al. (1994); (2) a plate cooler volume value based on milk production of 30 L d^{-1} cow^{-1} and 1.5 L of cooling water per L of milk for water not recycled within the barn (3) a cleaning cycle water value for parlour (17 L d^{-1}) and robotic farms (11 or 17L d^{-1}) for water not used for parlour wash down; (4) a bulk tank washwater volume value based on milk production of 30 L d^{-1} cow^{-1} and 0.05 L of washwater per L of milk, and; (5) a 4 L d^{-1} cow^{-1} volume value for miscellaneous water-use (House et al. 2014).

While relatively simplistic as noted in Box 3, the Nutrient Management software - based factors and equations embedded in WatBal-Dairy are responsive to water-use under a wide variety of dairy systems, management styles and recycling practices. To further enhance responsiveness, a "frequency of cleaning" field for bulk tanks was also included in the prototype to address situations, such as that found at Site A3, where milk pick-up is not a daily occurrence.

Washwater:	
= number of lactating cows ×	14 L for tie stall
	17 L for parlour system
	11 L for robotic system - brush teat cleaning
	20 L for robotic system - water teat cleaning
Plate Cooling Water:	
0 L for systems with complete plate cooling water recycling	
45 L x number of lactating cows for other systems	
Bulk Tank	
Yes = 1.5 L x number of lactating cows (for other systems)	
No = 0	
Parlour Wash Water (Recycled Water Use):	
Yes = 0	
No = number of lactating cows x	17 L for parlour system
	11 L for robotic system - brush teat cleaning
	17 L for robotic system - water teat cleaning
Miscellaneous Water Use:	
Yes = 4L x number of lactating cows for all systems	
No = 0	
Heat Abatement: (Based on Harner et al. 2013)	
Yes = 18.5 L d^{-1} (x number of days used)*	
No = 0	

Box 3 Factors and equations used in washwater calculations embedded into the WatBal-Dairy prototype adapted from the Ontario Nutrient Management software program (OMAFRA 2015) and Harner et al. (2013).

Heat abatement and the use of misting systems are another source of water-use on many farms. Notable variation in sprinkler designs, nozzle sizes and farm-specific characteristics make accurate determination of water-use difficult in the WatBal-Dairy format. In lieu of an equation, a static term of 18.5 kg d^{-1} of water-use is being employed in the prototype as recommended by Harner et al. (2013).

3.3.5. Statistical Evaluation

3.3.5.1. Evaluation of DNDC alfalfa model results

Alfalfa growth and crop water-use (ET), soil carbon and water dynamics were simulated in DNDC (Version DNDCv.CAN1) through the interaction of hundreds of co-dependent processes within the soil climate, crop growth and decomposition sub-models (Uzoma 2015). While local climate, soil, and management practices were inputted into the model, the default alfalfa growth algorithm, which is based on American measurements and cropping conditions (Li et al. 1992), was used in simulations.

To identify short-comings in the default alfalfa algorithm, modelled results for ET, NEE, biomass and soil moisture were analyzed relative to measured data from Site A1. Graphic exploratory analysis and the coefficient of determination (r^2) were used to identify trends and assess the degree of variance between the simulated and measured results. Root mean square error (RMSE) was also applied to assess DNDC model performance (Chai and Draxler 2014).

Pearson's correlation coefficient (r) was applied to simulated and measured ET, NEE and soil moisture results to determine if the variance in the modelled data could be attributed to specific environmental factors (temperature, precipitation, humidity and radiation); information which will be of interest when calibrating DNDC to Canadian conditions.

3.3.5.2. Evaluation of measured cattle, pasture and barn water-use

The identification of a 10-d thermoneutral period (September 25 to October 4, 2014) and a 10-d cool period (February 13 to 22, 2015) from metered data results facilitated a comparative statistical analysis of actual cattle intake and barn water-use at the study site (A3) and enabled identification of potential hotspots. Data results from the thermoneutral period were also used to statistically evaluate the strength of the WatBal-Dairy equation-based FWI and washwater results relative to actual water-use. Analysis included the use of graphic exploration, Pearson's correlation coefficient, descriptive and proportional statistics.

4. Results and Discussion

4.1. DNDC Alfalfa Simulations

4.1.1. ET Simulation

The accumulated daily ET from June 7 to November 5, 2014 (DOY 158 to 309), simulated by DNDC using actual weather and soil moisture conditions (Figure 8), was 331 mm compared to a measured value of 218 mm; an over-estimation of 113 mm or approximately 34.1% (Figure 9). Relative to ET estimates from existing literature which ranged from < 200 mm for arid conditions to > 1,000 mm for well-watered conditions (Table 3), these values appear to reflect drier conditions. However, the lower values may be attributed to: (i) the relatively short length of the growing season with planting occurring in late May; this was late relative to the norm for the EGLHLE, (i.e. almost a full month after alfalfa planting occurred at the farm study site -A3); (ii) the installation of the CPEC equipment 2 weeks after the planting preventing the recording of early development ET; (iii) the first-year status of the crop which favours allocation of water resources to root development during the early development stages (Moot 2012), and: (iv) the non-irrigated conditions. ET in rain-fed crops is generally lower than the potential ET. In contrast, ET in irrigated conditions, due to the increased availability of water, generally approaches or equals potential ET (Hoekstra 2013).

Additionally, in spite of applying the corrections noted in Appendix C to CPEC flux data, ET measurements were under-estimated by as much as 20% due to an energy imbalance. Closure of the energy balance, as discussed in Section 2.8, requires accurate estimates of the energy stored in the soil, air and biomass below the point of measurement (Leuning et al. 2012). However, even if the measurements were amended to account for the energy closure bias, DNDC would still over-estimate ET during the 2nd cut period (July 16 to September 1 - DOY 197-244 in Figure 9a) and post-2nd cut period (September 2 to November 2 - DOY 245-306). The ET for the first cut period (June 7 to July 15 (DOY 158-196) was 113 mm and 91.4 mm for DNDC and CPEC200, respectively. This produced a difference of only 19.1%. The 2nd cut ET was 134.6 mm and 78.5 mm for DNDC and CPEC200, respectively, producing a difference of 41.7%, and post-second cut ET was 83.4 mm and 48.1 mm, a difference of 42.3%.

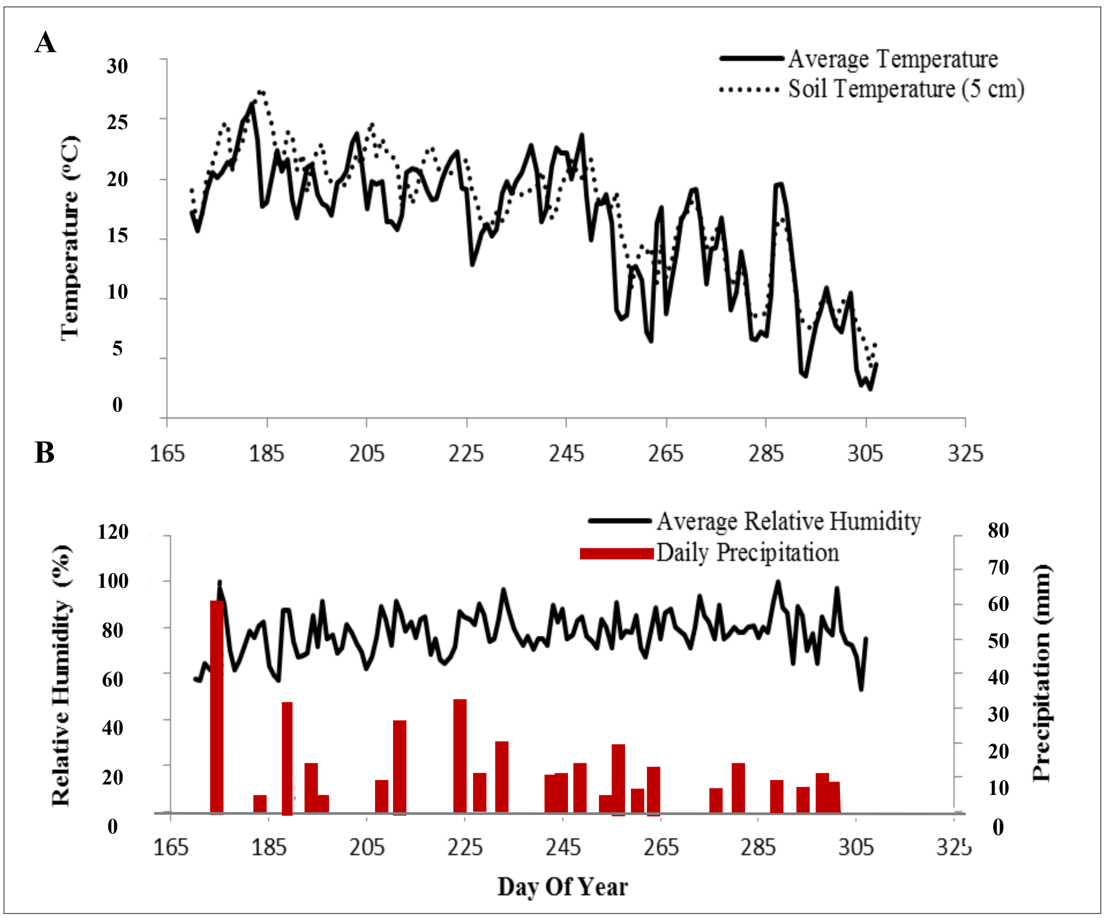

Figure 8 A: Mean daily temperature and mean daily 5 cm soil temperature recorded by the CPEC200 during the alfalfa growing season, June 19 to November 2, 2014 (DOY 170-306) B: Mean daily relative humidity and daily precipitation during the alfalfa growing season, June 19 to November 2, 2014 (DOY 170-306).

The degree of variance between the measured and modeled ET data, (Figure 9b), was statistically significant (r^2= 0.2; RMSE= 1.3 mm) with DNDC progressively over-estimating ET from early in the growing season. Similar escalation was noted by Dietiker et al. (2010) in a year-round cropping study in which DNDC over-estimated ET during maturation of the main crop (winter wheat, winter barley and potato rotation) in 5 out of 6 years. However, Sansoulet et al. (2014) reported an improvement in the agreement between measured and modeled values throughout the growing season (r^2 = 0.78), when employing a calibrated version of DNDC to estimate spring wheat ET in Eastern Canada. Similarly, in a 2013 Eastern Ontario study comparing CPEC200 ET in soybeans to DNDC estimates (Piquette 2014, unpublished), simulated values closely matched measurements with an under-estimation of only 2.8% (r^2 =0.82; RMSE =0.59 mm).

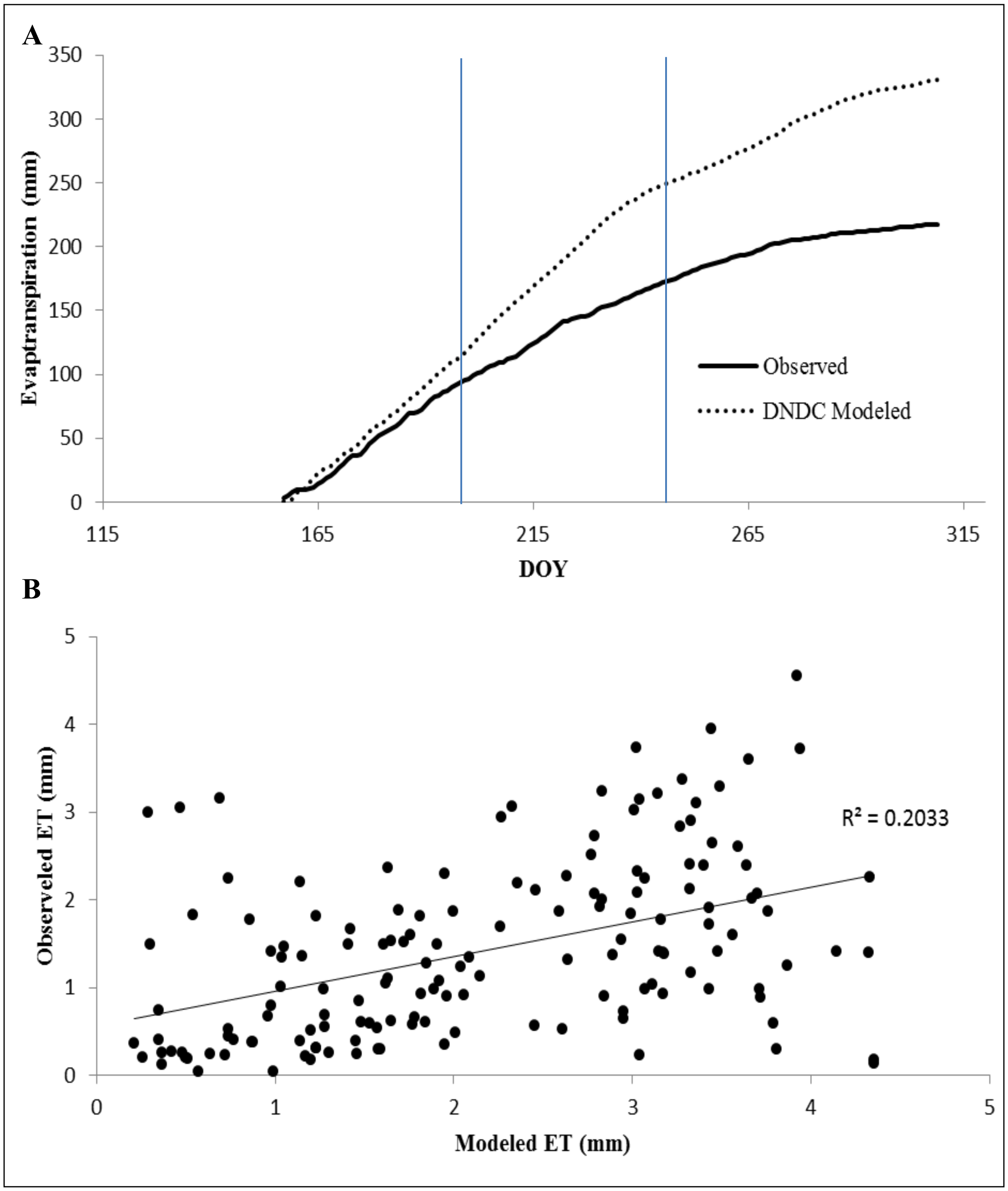

Figure 9 A: Comparison of DNDC daily ET estimates and observed CPEC200 eddy covariance ET measurements for alfalfa growth at site A-1 from June 5 to November 7, 2014 (DOY 156-311) with vertical lines indicating crop cut dates. B: Regression analysis of the DNDC estimated ET and observed CPEC200 eddy covariance ET measurements for alfalfa growth at site A1 from June 19 to November 2, 2014 (DOY 156-311).

4.1.2. NEE Simulation

DNDC provided a seasonal NEE uptake of 4,123 kg C ha^{-1} compared to 3,636 kg C ha^{-1} measured with the CPEC200 for the 152-d growing period (June 7 to November 5, 2014 - DOY 158-309) (Figure 10). This represented an over-estimation of 11.8% for the growing season. The high degree of variance between the daily measured and modeled results ($r^2 = 0.30$; RMSE= 29.71 kg C $h^{-1}d^{-1}$) (Figure 10b) was strongly impacted by DNDC's continued simulation of C uptake subsequent to cuttings and during the late autumn senescence period (Figure 10a) as well as an under-estimation of NEE uptake throughout the early maturation period (June 7 to July 19 - DOY 158-260). Dietiker et al. (2010) also reported an under-estimation of NEE during the maturation period for rapeseed and winter wheat but reported an over-estimation for potatoes. The Eastern Ontario soybean study (Piquette 2014, unpublished) that used a calibrated DNDC model also simulated an over-estimation of NEE relative to measured values throughout the majority of the growing season. It is important to note that while the difference in daily DNDC and measured NEE values appear significant, annual model estimates within 1,000 kg C h^{-1} $year^{-1}$ are considered to realistically predict seasonal trends and the absolute magnitude of the CO2 fluxes (Dietiker et al. 2010). In this study, the difference between measured and modelled values was 486.51 kg C ha^{-1} for the season.

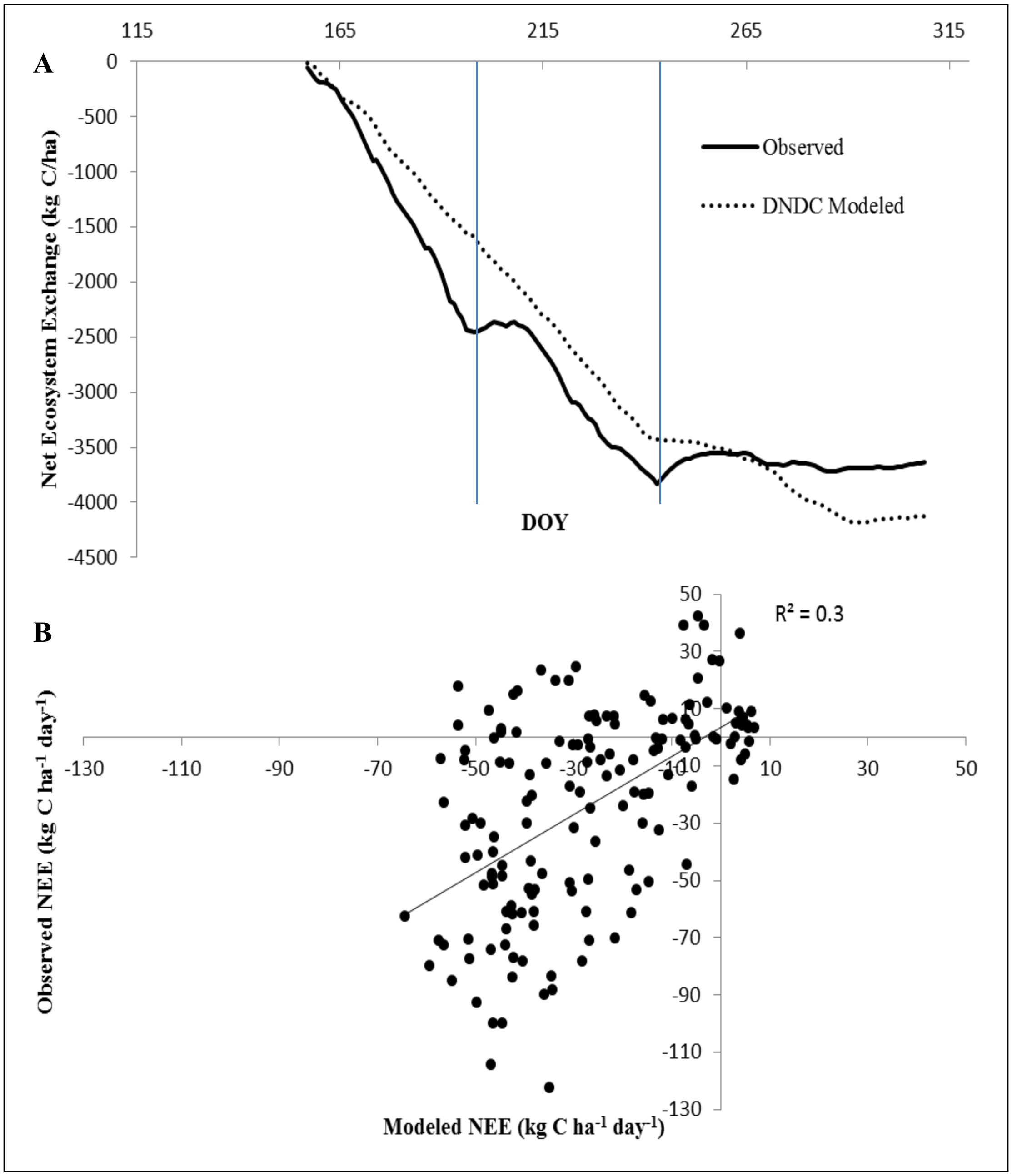

Figure 10 A: Comparison of DNDC daily NEE estimates and observed CPEC200 eddy covariance NEE measurements for alfalfa growth at Site A1 from June 5 to November 7, 2014 (DOY 156-311) with vertical lines indicating crop cut dates. B: Regression analysis of the DNDC estimated NEE and observed CPEC200 eddy covariance NEE measurements for alfalfa growth at Site A1 June 5 to November 7, 2014 (DOY 156-311).

4.1.3. *Biomass Simulation*

The DNDC estimate of total alfalfa biomass production, which included two harvests and standing alfalfa at the end of the growing season, was 4,048.5 kg DM ha^{-1}. The actual yield was 3,654.4 kg DM ha^{-1} which represented a difference of 394.1 kg DM ha^{-1}. Both values fell below the OMAFRA 2014 yield average of 5,700 kg DM ha^{-1} (OMAFRA 2015a). This may be the result of the late sowing date of the first year crop. DNDC predicted a faster rate of biomass development subsequent to sowing than the measured rate but under-estimated total biomass production throughout the first cut period by 37.6 kg DM ha^{-1} (1,438.4 measured vs. 1,400.8 kg DM ha^{-1} DNDC) (Figure 11a). The rapid post-seeding growth simulation was similar to Kröbel et al. (2011) for spring wheat grown in Saskatchewan and Québec when using growth algorithms that were not calibrated for Canadian conditions. During the 2nd cut growth phase, DNDC continued to simulate rapid growth while the actual growth rate slowed as the plant bloomed and approached full-maturity. As a result, DNDC over-estimated yield by 179 kg DM ha^{-1} (1,459.2 kg DM ha^{-1} measured vs. 1,638.5 kg DM ha^{-1} DNDC). Subsequent to the 2nd cut, DNDC began to under-estimate the rate of biomass development but then showed notable over-estimation relative to the actual measurements until the end of the study period. The measured results are indicative of autumn senescence. Overall, however, as indicated by Figure 11, there was a strong correlation (r^2 =0.84; RMSE= 215.96 kg DM ha^{-1}) between the measured and modeled results. The high accuracy of the biomass simulation was similar to the results of other studies including a study by Zhang et al. (2002) in which DNDC estimations were strongly correlated to measured data for winter wheat (r =0.89) and rice (r=0.91); a US study in which corn and soybean biomass were estimated within 12% of the observed accuracy (David et al. 2009), and; several Canadian spring wheat studies using Canadian-based algorithms (Kröbel et al. 2011; Sansoulet et al. 2014). Results from this study were better than those detailed by Kröbel et al. (2011) for four treatments of spring wheat which had r^2 values ranging from 0.45 to 0.79 and a mean RMSE of 1,395 and 969 for non-calibrated and calibrated DNDC simulations, respectively. Overall, from a cut segment and full-season perspective, although not yet calibrated to Canadian conditions, DNDC estimates were of sufficient accuracy to warrant use in Watbal Dairy.

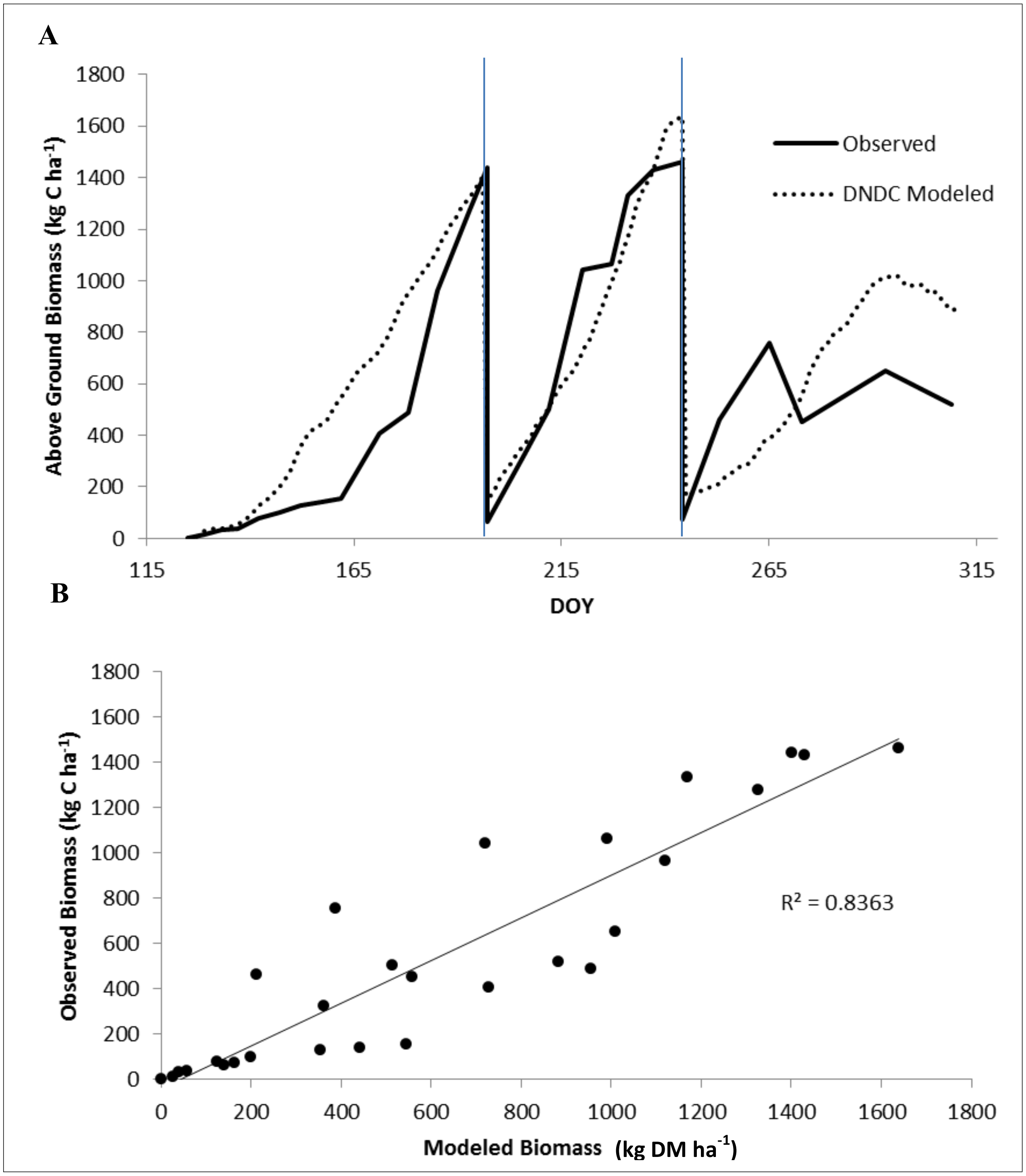

Figure 11 A: Comparison of DNDC daily biomass estimates and in-situ biomass measurements of alfalfa in kilograms of dry matter per hectare at site A1 June 5 to November 7, 2014 (DOY 156-311) with vertical lines indicating crop cut dates. B: Regression analysis of the daily DNDC estimated biomass growth and *in situ* daily biomass growth measurements of alfalfa biomass in kilograms of dry matter per hectare at site A1.

4.1.4. Soil Moisture Simulation

The overall variance between the 5 cm TDR probe volumetric water content readings and the 5 cm DNDC modeled results was significant (r^2 =0.28). However, the variance was influenced by DNDC's over-estimation of volumetric water content on July 11 (DOY 192), August 13 (DOY 225) and October 21 (DOY 294) and a slight under-estimation on September 4 (DOY 247) (Figure 12a). No patterns emerged between the DNDC simulation and actual precipitation to fully account for these variances. The over-estimates were associated to 3-d rain accumulation of 2 mm (July 11 - DOY 192), 55 mm (August 13 - DOY 225) and 7 mm (October 21 - DOY 294), while the under-estimation was linked to a 3-d accumulation of 15.4 mm (September 4 - DOY 247). It may therefore be assumed that DNDC simulations were potentially influenced by other climate variables, soil properties, and/or plant characteristics and water-use requirements.

In comparison to the average daily CS616 horizontal probe measurements, DNDC underestimated volumetric soil moisture at 5cm by 12%. As noted in Figures 8a and b, while there is apparent similarity in the trend patterns, the overall variance in the data was significant (r^2 =0.25; RMSE = 8.0 mm) with the percentage of daily difference ranging from <1% to 50.1%. Generally, it was noted that the variance was reduced in periods of higher moisture content. Notable deviation occurred October 2 (DOY 275) when the probes showed increasing volumetric water content in response to precipitation events and reduced crop needs while DNDC simulated decreasing volumetric water content. In contrast to these results, DNDC over-estimated soil moisture in a Manitoba wheat study by Uzoma et al. (2015) which employed a Canadian calibrated version of DNDC. Over-estimations ranged from 1.3% in wet seasons (precipitation > 80th

percentile of the 30 year normal growing season precipitation of 399 mm) to a maximum of 11.5% in dry seasons (precipitation < 20^{th} percentile of the 30 year normal growing season precipitation). Generally, DNDC also showed less variability to measured values in this study during periods of higher moisture content. This was attributed to the failure of DNDC to characterized soil cracking induced preferential flow during dryer periods (Uzoma et al. 2015).

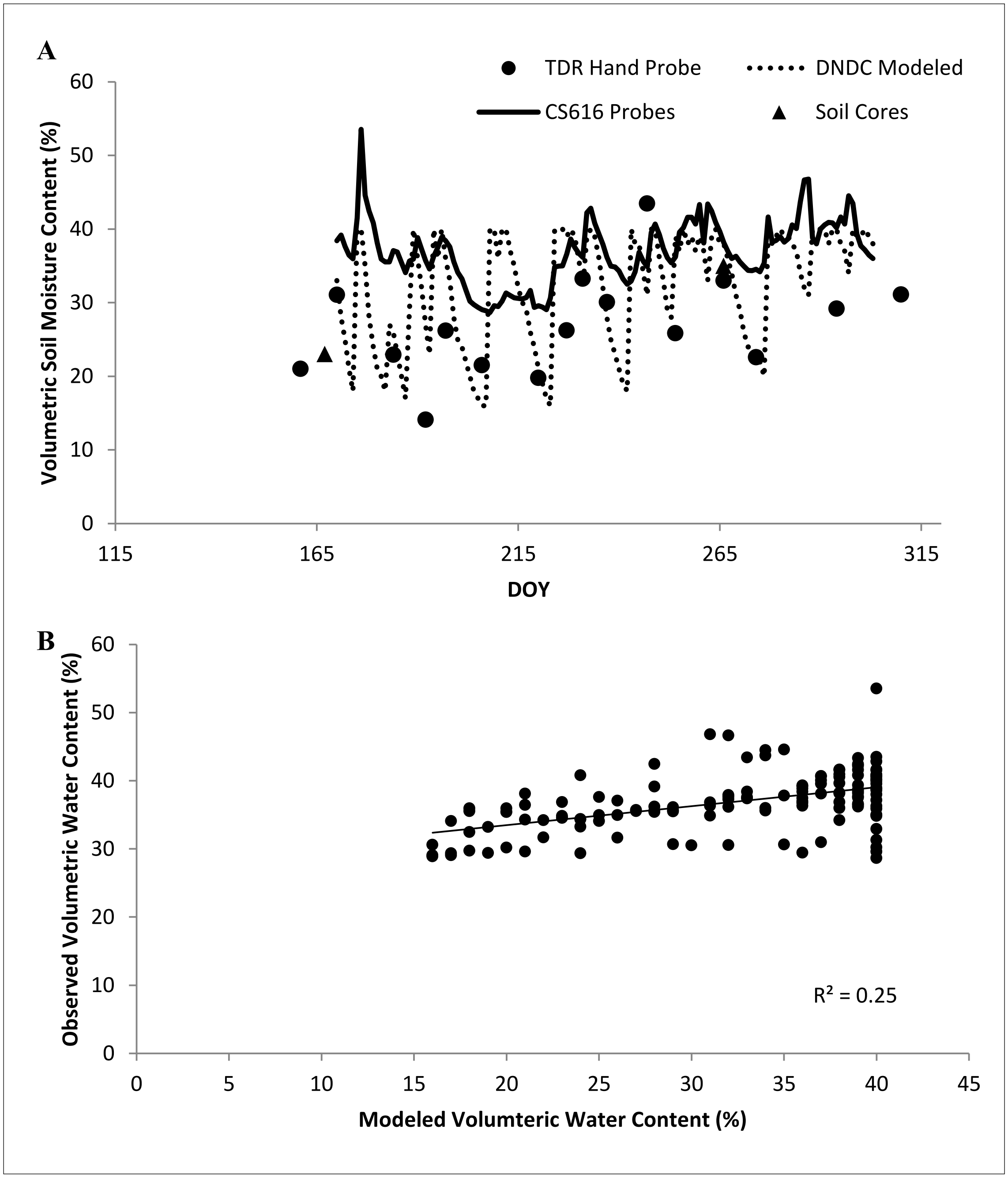

Figure 12 A: Comparison of DNDC volumetric soil moisture estimates and in-situ volumetric soil moisture measurements at 5cm depth from site A1 measured using the TDR hand held probe, CS616 probes and gravimetric soil cores, during 2014 growing season. B: Regression analysis of the DNDC estimated volumetric soil moisture and *in situ* CS616 measurements of soil moisture at 5cm depth at site A1 during the 2014 growing season.

4.2. Water-Use Efficiency

The WUE was calculated based on the DM yield for each growth segment to the time of cutting, as well as the full season, using both simulated and measured data (Table 15). For the first, second and full cut periods; the simulated results were lower than the measured WUE by 20.5%, 34.4%, and 27.4%, respectively. The lower simulated DNDC WUE, which showed similarity to the low end measurements from Attram's (2013) Alberta alfalfa study (13.0, 12.1, 11.7 kg ha^{-1} mm^{-1}), was largely the result of the over-estimation (34.1%) of ET by the model relative to measured values.

In contrast to the variability of the measured WUE results (15.7, 18.6 and 16.8 kg DM ha^{-1} mm^{-1}), DNDC results were consistent (12.4, 12.2, 12.2 kg DM ha^{-1} mm^{-1}). While further study is required, it is possible that this consistency resulted from a pre-determined empirical relationship in DNDC; there is a dependent relationship in the model between the estimation of the crop water requirement which drives the simulation of transpiration and estimates of crop biomass (Sansoulet et al. 2014).

With regard to measured WUE values, although site A1 was a first year stand in Ontario, the 1st cut value (15.7 kg C ha^{-1} mm^{-1}) fell within the limits described for the 1st cut of second year alfalfa growth in Alberta (13.0 – 16.3 kg $ha^{-1}mm^{-1}$) while the 2nd cut WUE (18.6 kg ha^{-1} mm^{-1}) exceeded the observed Alberta 2nd cut range of 12.1 to 15.7 kg $ha^{-1}mm^{-1}$ (Attram 2014). The observed values were also in the range of measurements for 8 locations in the USA for 1st to 3rd year crops (15.2 ±2.1 kg $ha^{-1}mm^{-1}$) (Schaeffer et al.1988); but, values were lower than the six year mean of 21 kg $ha^{-1}mm^{-1}$ reported for non-irrigated 'dryland' growth (ET = 414 mm) in Saskatchewan (Jefferson and Cutforth 2005). The latter report, however, showed a range of 15 kg $ha^{-1}mm^{-1}$ to 26 kg $ha^{-1}mm^{-1}$

over the course of the study: a range indicative of the potential variance in WUE for a single plant type due to the oscillating impact of climate, plant genetics, soil characteristics and management practices on ET (Allen et al. 1998; Irmak 2009; ARRD 2013).

Table 15 Results for water-use efficiency calculated from crop biomass and evapotranspiration estimates from DNDC and *in situ* measurements at site A1. 1st cut includes June 7 to July 15 (DOY 158-196), 2nd cut includes July 16 to September 1 (DOY 197-244) and whole season includes June 7 to November 5 (DOY 15-309).

	Yield (kg wet biomass ha^{-1})	**Yield (kg dry biomass ha^{-1})**		**ET (mm)**		**WUE (kg DM ha^{-1} mm^{-1})**	
	Measured	Measured	DNDC	Measured	DNDC	Measured	DNDC
1st cut (DOY 158 – 197)	17,053	1,438.4	1,400.8	91.4	113.0	15.7	12.4
2nd cut (DOY 198 – 244)	18,240	1,459.2	1,638.5	78.5	134.6	18.6	12.2
Whole season* (DOY 158 – 309)	42,340	3,654.4	4,047.5	218.0	331.0	16.8	12.2

*Whole season includes both cuts plus standing biomass at end of season

4.3. Analysis of DNDC Simulation Results

The variations between *in situ* measurements and DNDC simulation results for biomass, ET, NEE and soil moisture were indicative of the uncertainty associated with modeled predictions noted in Section 2.9 (ISEOS 2012). Specifically, uncertainty was associated to the use of the default growth algorithms; defects in algorithm responsiveness; defects in the scientific basis; and potential error in data input.

Default algorithms in DNDC, developed from American-based measurements and cropping systems, have been identified as a source of error in crop and flux simulations due to their inability to accurately reflect regional conditions in other countries (Kröbel et al. 2011; Uzoma 2015). In this study, the use of the default alfalfa growth algorithm was considered the primary source of error in DNDC simulations.

The overall biomass estimate was generally favourable relative to measured values; but, as previously noted, DNDC over-estimated biomass development during: (a) the early growth stage of the initial cut; (b) immediately subsequent to the second cut, and (c) during the period of senescence. It appears that in the first instance, the default algorithm may have over-partitioned shoot (stem and leaf) and grain biomass relative to root biomass production. In first-year alfalfa crops, above-ground biomass is generally reduced from sowing to the first cut due to the preferred allocation of water resources to root development (Moot 2012). In the second instance, the algorithm failed to account for the decline in leaf area, and subsequently ET, that occurs as the plants bloomed and reached maturation prior to the second cut. Finally, in the third instance, the continued production of above-ground biomass during senescence was indicative of algorithms programmed to reflect a longer growing season than that typical of Canadian conditions. The inability of the model to detect the period of senescence may also be related to a flaw in the scientific basis that underlies the model algorithm. In DNDC, crop growth is driven by temperature with no consideration given to changes in radiation. Dietiker et al. (2011) noted autumn temperatures favour biomass development in DNDC; if consideration is not given to the reduction in photosynthetic activity brought about by a decrease in daily radiation, an over-estimation will result.

The over-estimation of ET in DNDC was empirically related to the biomass over-estimation. Actual transpiration in DNDC is simulated from the shoot (stem and leaf) water requirement (g water g^{-1} shoot biomass) which is dependent on the quantification and partitioning of crop biomass and water uptake from the soil root layers. There was an apparent association noted between shoot biomass quantification and ET; particularly, in the post-cut senescence period when measured ET accumulation slowed. Actual evaporation is also impacted by biomass production with the stage and extent of plant growth impacting the available soil moisture (ISEOS 2012). DNDC simulations of evaporation are driven by the available soil moisture in the top 15cm of the soil profile and the extent of crop residue (Sansoulet et al. 2014).

Of interest, as discussed in Section 2. 4.1, there is an established positive correlation between ET and both air temperature and solar radiation (Brouwer and Heibloem 1986; Irmak 2009), and a negative correlation between ET and relative humidity (Allen et al.1998; Osman 2013). While DNDC ET simulations reflected the relationship to temperature (r= 0.58), there was a notably weaker correlation to radiation (r = 0.43) and humidity (r- 0.03) in comparison to measured values (r= 0.66; r= -0.28)

(Table 16). With temperature being the only climatic variable driving estimations of biomass, and ET being strongly influenced by biomass, this was not an unexpected result.

Table 16 Correlation of environmental variables (air temperature, precipitation, relative humidity, net solar radiation) to daily DNDC ET, NEE and 5 cm volumetric soil moisture estimates, daily in-situ CPEC200 ET and NEE measurements and CS616 volumetric water content (VWC) of soil at 5cm depth at site A1 during the 2014 growing season.

Environmental Parameter	Measured Environmental Variable	Pearson Correlation Coefficient (r)	
		Measured	*DNDC Modelled*
ET	Air Temperature (ºC)	0.57	0.58
	Precipitation (mm)	0.22	0.19
	Relative Humidity (%)	-0.28	-0.03
	Net Solar Radiation (MJ m^{-2} d^{-1})	0.66	0.43
NEE	Air Temperature (ºC)	-0.39	-0.62
	Precipitation (mm)	-0.16	-0.10
	Relative Humidity (%)	0.19	0.07
	Net Solar Radiation (MJ m^{-2} d^{-1})	-0.46	-0.45
5 cm VWC	Soil Temperature (ºC)	-0.43	-0.39
	Precipitation (mm)	0.31	0.18

Estimation of NEE fluxes in DNDC is based on the net sum of the gross primary production of plant (root and shoot) autotrophic respiration (kg C ha^{-1} d^{-1}) and soil microbial heterotrophic respiration (kg C ha^{-1} d^{-1}) (Abdallah et al. 2013). Quantification of plant respiration is directly dependent on the extent of simulated crop growth while modeled soil respiration is based on the quantity and quality of the soil organic carbon pool, particulars from the soil climate profile and soil nitrogen availability (ISEOS 2012). The over-estimation of NEE in the senescence period reflects the corresponding over-estimation of biomass by the default growth algorithm. However, with sol respiration decreasing with lower moisture levels (Suseela et al. 2012), it is also likely that the higher uptake values during senescence were influenced by the under-estimation of soil moisture. The inability of the default growth algorithm to adequately model biomass production after harvest also impacted the NEE simulations. While measured NEE intake levels decreased slightly subsequent to cuttings, DNDC simulated a continued increase in NEE accumulation. Overall, with the exception of temperature, the correlation of the NEE estimates to climatic variables closely resembled the measured correlation values (Table 16). The stronger negative correlation of the modeled results to temperature (r= -0.62) relative to the measured results (r= -0.39) reflected the relationship between simulated NEE and temperature-driven biomass results.

As previously noted, soil moisture simulation in DNDC is influenced by the stage and extent of biomass production (ISEOS 2012); higher biomass quantities generally place higher demand on soil moisture. As such, it is assumed that the progressive over-estimation of biomass by the default algorithm likely contributed to the under-estimation of soil moisture. Based on the weak positive correlation between precipitation and both measured (r= 0.31) and estimated soil moisture (r= 0.18) and the moderate negative correlation to soil temperature (r= -0.43; r= -0.39) (Table 16), it is also possible that the uncertainty of the soil moisture simulation was influenced by inputs reflecting soil properties. Specifically, there is a positive correlation between organic matter and the water holding capacity of a soil (Brown 2009; Osman 2013). It is possible that the input values for soil organic carbon used in the simulation failed to adequately reflect the water holding capacity of the study site soil resulting in the lower soil moisture values. The quantification of soil organic content was over-looked in this study; input values were supplied by the AAFC modellers based on data from previous studies conducted at the site (A1).

Overall, it can be reasonably assumed that many of the uncertainties in the DNDC simulations in this study were related to the use of the default growth algorithm which led to the inaccurate modelling of biomass partitioning and the associated growth curve. In contrast to these results, results from recent Canadian studies, which have employed a regionalized algorithm with empirical growth curves for cool season corn, soybean and winter wheat, have shown improvement in the overall quality of DNDC simulations (Kröbel et al. 2011; Smith et al. 2013; Grant et al. 2014; Sansoulet et al. 2014; Uzoma et al. 2015).

While it is recognized that calibration of models require multiple years of measured data, the short-comings in the existing simulation and identified benchmarks from *in situ* measurements will support the creation of an empirically fitted growth curve, biomass fractioning and C/N ratios specific to alfalfa growth in Canadian climatic conditions in DNDC. To further enable this development, data from experiments conducted throughout this study, including measurements not presented or analyzed in this report, were made available to modellers at AAFC (Appendix K).

4.4. Cattle, Pasture and Barn Measurements

4.4.1. Metered Inputs

For inputs, the total metered water-use for confined and pastured cattle and milkhouse cleaning was 54,646 kg and 45,206 kg for the 10-d thermoneutral and cool periods respectively. Water-use in the thermoneutral period was divided between FWI at 87.8% and washwater at 12.2%, while the cool season partitioning was 77.8% FWI and 22.2% washwater (Figure 13).

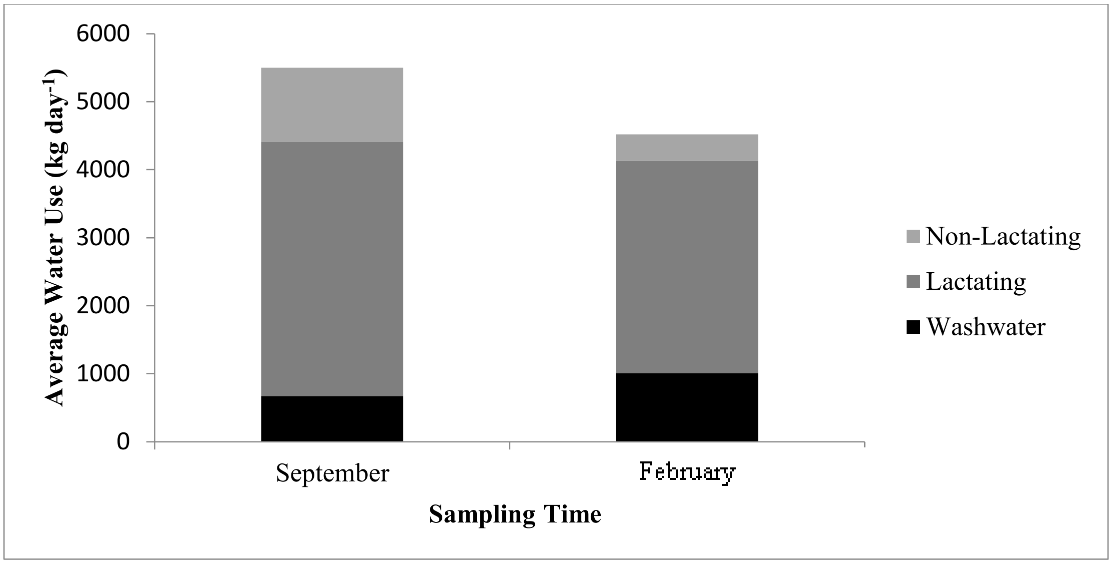

Figure 13 Comparison of metered water-use (kg d^{-1}) for pastured and confined lactating cows, heifers and dry cows and milkhouse washwater at the Morewood, Ontario study site (Site A3) between the September 25 to October 4, 2014 (DOY 268-277) thermoneutral period and the February 13 to February 22, 2015 (DOY 44-53) cool period.

The placement of meters allowed for the identification of daily water-use by location (barns, yard, milkhouse and pasture) for the study periods (Figures 14a and b). In the thermoneutral period, total daily FWI for all animal groups ranged from 4,331 kg d^{-1} to 5,140 kg d^{-1} with a mean of 4,792 kg d^{-1}, and washwater ranged from 570 kg d^{-1} to 874 kg d^{-1} with a mean of 673 kg d^{-1}. Most of the FWI was associated with exterior water consumption within the yard (71%) and pasture (15%) environments accounting for a daily average 86% (4,121 kg d^{-1}), while the milking barn (6.6%) and the back barn with young heifers (7.4%) were minor components of total intake. FWI had a strong positive correlation to the daily mean outdoor temperature (r = 0.55) and daily outdoor maximum temperature (r =0.63) in agreement with studies by Murphy et al. (1983), West (2003) and Olkowski (2009). There was also a strong negative correlation between FWI and humidity (r = -0.58) similar to the findings of the USA National Research Council

(2001). The two days of highest relative humidity (93.8% and 89.4%) (and lowest mean temperature at 12.0 and 11.4 ºC respectively) in this study corresponded with the lowest water intake (4,331. kg d^{-1} and 4,387 kg d^{-1}).

Daily FWI in the cool period ranged from 3,204 kg d^{-1} to 3,824 kg d^{-1} with an average intake of 3,516 kg d^{-1} and washwater ranged from 821 kg d^{-1} to 1175 kg d^{-1} with a mean of 1,005 kg d^{-1}. On average, lactating cows and calves in the main barn accounted for 88.8% of total daily FWI (3,122 kg d^{-1}) with the remaining water being allocated to dry cows and heifers in the back barn. As expected, cooler temperatures reduced FWI relative to the thermoneutral period (Broucek et al. 1991; Tarr 2010); however, there was only a moderate positive correlation (r =0.48) between cattle intake and the mean daily temperature and a modest negative correlation (r = -0.17) between the daily high temperature and the total FWI.

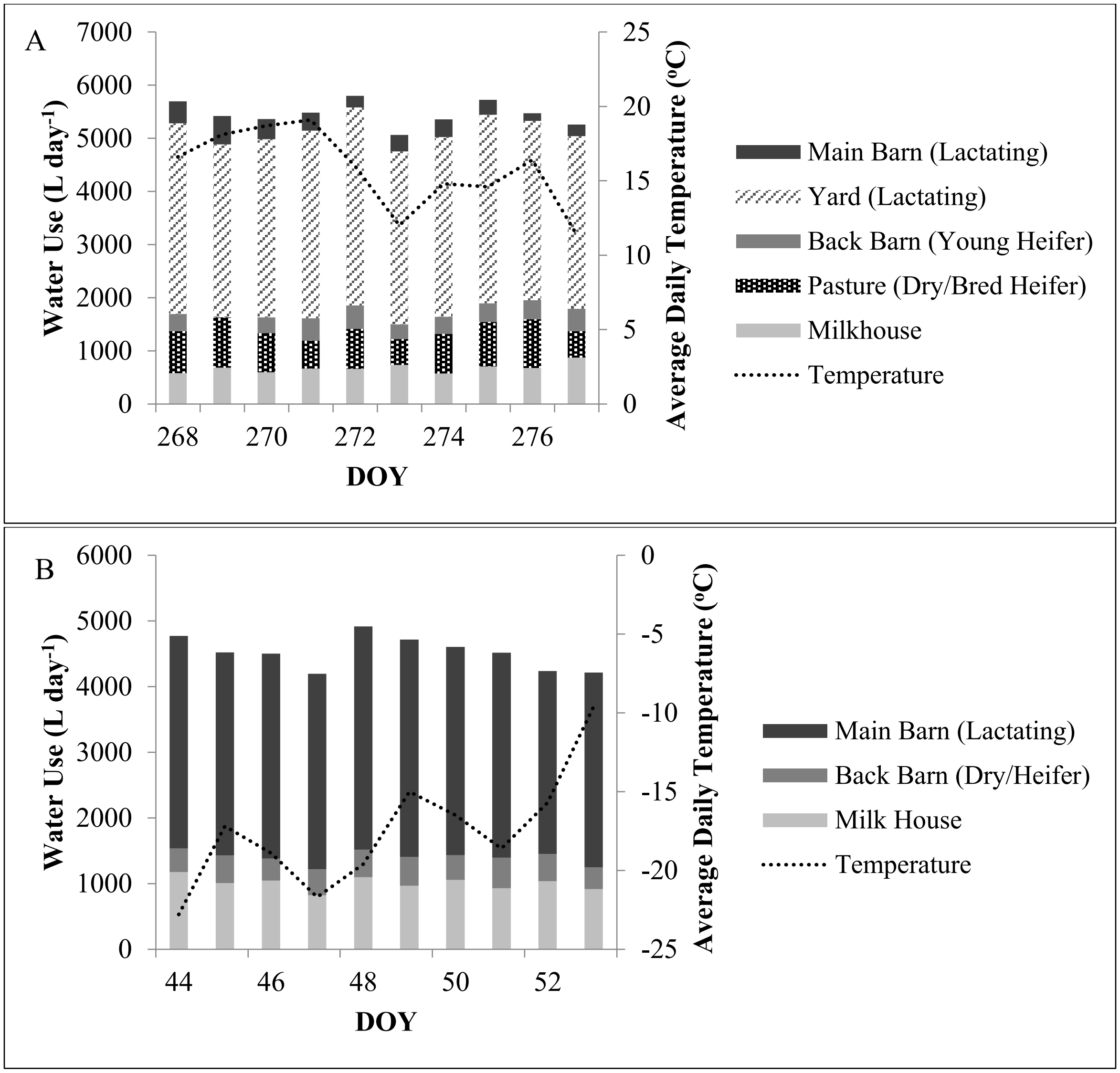

Figure 14 A: Water-use (L d^{-1}) by location with temperature from the Morewood, Ontario study site (Site A3) as determined through *in situ* measurements for the September 25 to October 4, 2014 (DOY 268–277) thermoneutral period. Excludes September 26 (DOY 269) back barn data – measurement corrupted by unknown causes. B: Water-use (L kg^{-1})by location with temperature from the Morewood, Ontario study site (A3) as determined through *in situ* measurements for the February 13 to February 22, 2015, (DOY 44-53) cool period.

In comparing the two study periods, the overall water-use decreased from the thermoneutral period to the cool period by 1,276 kg d^{-1}; a 26.6% reduction. The decrease reflects the 16.6 % decline in the total water consumed by lactating cows and calves in the milking barn and a 63.7% decline in total water consumed by dry cows and heifers (back barn and pasture in thermoneutral period vs. back barn in cool season). The decreases in intake, which are discussed in detail further in this section, have been offset by a 33% increase in washwater use. Washwater volumes should be relatively constant throughout the year with consistent management practices (Harner et al. 2013); but, at the study site there was an average 331 kg d^{-1} increase during the cool period. Discussions with the farmer indicated no change in management practices between the two study periods. In considering the hourly milkhouse readings for both periods, however, it appears that the difference in metered water-use may be attributed to a pipeline malfunction. During the thermoneutral period, there is almost no water-use between: (a) pipeline cleanings on September 27 (DOY 270) and September 29 (DOY 272); (b) between the pipeline and bulk tank cleanings on September 28 (DOY 271), and; (c) during quiet times (Figure 15). In contrast, water-use during February 14 to 16 (DOY 45 to 47) of the cool period never goes to zero. Leaks in pipelines and fittings may be responsible for significant water-use on a daily basis. In a technical report by Brugger and Dorsey (2008) examining water-use on a large Ohio dairy farm (854 to 1005 cows), a faulty valve resulted in a loss of 32,706 kg d^{-1}, while a broken trough float produced significant over-flow loss. In this study, a leak of 0.23 kg min^{-1} over the 10-d cool period could explain the additional 331 kg d^{-1} washwater use.

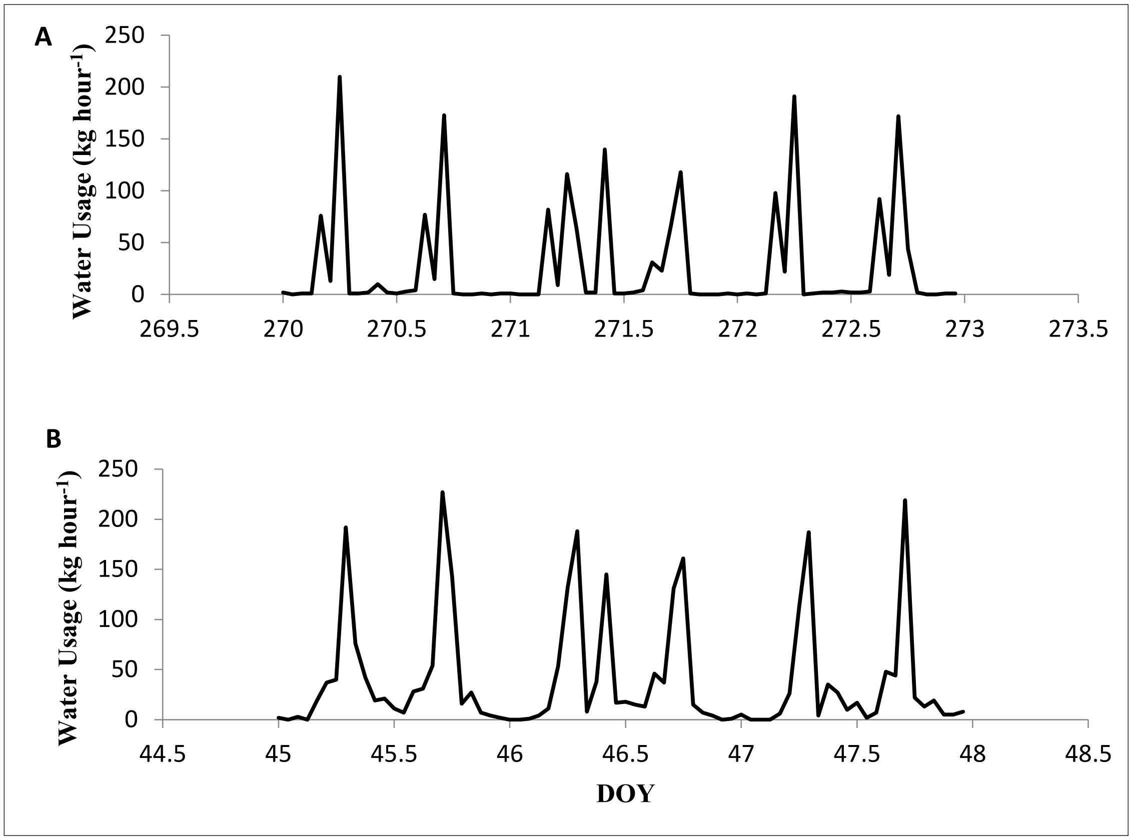

Figure 15 A: Hourly metered milkhouse water use readings from the Morewood, Ontario study site for September 27 to 29, 2014 (DOY 270 to 272) of the thermoneutral period with daily milk pipeline and bi-daily bulk tank cleaning reflected in trends B: Hourly metered milkhouse water use readings from the Morewood, Ontario study site for February 14 to 16, 2015 (DOY 45 to 47) of the cool period with daily milk pipeline and bi-daily bulk tank cleaning reflected in trends.

4.4.2. Free Water Intake by Cattle Group

To enable calculation of daily water consumption by cattle life-stage from metered data, several assumptions were required. First, in the main barn where water was shared by lactating cows and calves during both periods, calves were allotted 9 kg d^{-1} cow^{-1} of the metered result based on existing OMAFRA recommendations (Ward and McKague 2015). Second, in the pasture, the division of shared water resources between dry cows and bred heifers was based on the median of the dry cow intake scale provided by OMAFRA (Ward and McKague 2015) (41.5 kg d^{-1} cow^{-1}), and a feasibility assessment of the resulting heifer intake value including consultation with the dairy farmer. The appropriateness of these allocations is discussed later in this section. Additionally, water-use in the back barn during the cool period was not partitioned due to the difficulty in allocating the low total metered water-use between dry cows, bred and young heifers. This is also discussed further below.

Partitioning of FWI for each cattle class is shown in Table 17. In the thermoneutral period, consumption by 33 lactating cows (3725 kg d^{-1}) accounted for 77.2% of the total cattle FWI with the majority of the intake occurring in the yard (92%). The average daily water consumption of 113 kg d^{-1} cow^{-1} was very similar to OMAFRA estimates of 115 kg d^{-1} cow^{-1} (Ward and McKague 2015) and USA study estimates of 109.02 kg d^{-1} cow^{-1} (Harner et al. 2013). The measured value was also within 11 kg d^{-1} of Adams and Sharpe's (1995) modified Kertz equation (eqn 11) result of 124.3 kg d^{-1}. There was a significant decrease in daily free water consumption (17.8%) between the two study periods with cool period intake by 35 lactating cows falling to 89 kg d^{-1} cow^{-1} in spite of a 29.7% increase in DMI; yet, the portion of the total farm FWI (3104 kg d^{-1}) attributable to lactating cows rose to 88.7%. The daily FWI fell to the low end of the 87 to 102 kg d^{-1} cow^{-1} range reported by OMAFRA (Ward and McKague 2015); but, is greater than the 80 kg d^{-1} cow^{-1} estimated by Amaral-Philips et al. (N.D.) for lactating cows in temperatures ranging from -12.2 to 4.4ºC, and the Looper and Waldner (2002) estimate of 83 kg d^{-1} for a cow producing 27.2 kg d^{-1} of milk in 4.4ºC conditions. Cows at the study site produced 26.5 kg d^{-1} cow^{-1} in temperatures averaging -12.3ºC. Additionally, the measured value exceeds the water budgeting recommendation developed by Harner et al. (2013) which suggests that FWI should be assessed as three times the milk yield which in this study would lead to an estimate of 80 kg d^{-1} cow^{-1}. The Murphy et al. (1983) FWI equation for early stage lactating Holstein cows (eqn 6) provided the closest estimate at 102 kg d^{-1} cow^{-1}, a difference of 13 kg d^{-1} cow^{-1}. As a two- variable equation based on DMI and milk yield, the higher value is not unexpected in view of the increased feed intake required for energy production during the winter months.

Table 17 Average daily water-use data by location and cattle group based on metered measurements at the Morewood, Ontario, farm study site (A3) and OMAFRA water requirement estimates combined with ration water intake as determined through farmer consultation for the identified thermoneutral and cool evaluation periods.

Thermoneutral Season (September 25 to October 4, 2014 - DOY 268-277) *							
Farm Area	Specific Water-use	Number of Animals	Total Free Water Intake (FWI) (kg d^{-1})	Water-use on Whole Farm Basis (%)	Free Water Intake by Animal (kg d^{-1})	Ration Water Intake (RWI) by Animal (kg d^{-1})	Total Water Intake by Animal (kg d^{-1})
Milk Barn	Lactating Cows Barn (a)	33	299				
	Lactating Cows Yard (a)		3426				
	Total Lactating Cows (a)		3725	68	113	12	125
	Calves (b)	2	18	0.3	9	3.5	13
	Total Barn (a/b)		3743				
Back Barn	Heifers 2-17 months (a)	16	358	7	22	3	25
	Total Back Barn (a)		358**				
Pasture	Dry Cows (b)	10	415	8	42	39	79
	Heifers 17-24 months (c)	13	311	5	24	28	52
	Total Pasture (a)		726				
Milkhouse	Total Washwater (a)		673	12			
TOTAL			5500				
Cool Season (February 13 to February 22, 2015 - DOY 44-53) *							
Milk Barn	Lactating Cows (a)	35	3104	69	89	14	103
	Calves (b)	2	18.0	0.4	9	4	13
	Total Milk Barn (a/b)		3122				
Back Barn	Dry Cows	4				10	
	Heifers 17-24 months	12				9	
	Heifers 2-17 months	19				4	
	Total Back Barn (a)		394	9			
Pasture	Total Pasture		n/a				
Milkhouse	Total Washwater (a)		1005	22			
TOTAL			4520				

* 1 litre of water = 1 kg of water in all calculations. All quantities have been rounded to the nearest kg ** Excludes September 26 (DOY 269) data – corrupted by unknown causes
(a) Metered measurements (b) Based on OMAFRA estimates (c) Based on difference in Total Pasture and Dry Cow FWI

The in-barn calf FWI was insignificant in this study with 2 calves (0 to 2 months, 45 to 90 kg) accounting for 0.3% (18 kg d^{-1} cow^{-1}) and 0.4% (18 kg d^{-1} cow^{-1}) of total FWI in the thermoneutral and cool periods respectively. This was based on the OMAFRA recommendation of 9 kg d^{-1} for both the thermoneutral and cool period which is the median of the FWI range of 4.5 to 13 kg d^{-1} cow^{-1} for cattle age 1-4 months (Ward and McKague 2015). The estimate fell within the range of 4 to 11 kg d^{-1} cow^{-1} proposed by Looper and Waldner (2002) for calves in the 45 to 90 kg weight class, and fell to the high end of the range of 5 to 9 kg d^{-1} cow^{-1} for heifers in the 1-2 month range proposed by Adams and Sharpe (1995).

The 16 young heifers (2 to 17 months) in the back barn were responsible for 7.4% (358 kg d^{-1}) of the total FWI in the thermoneutral period, consuming an average of 22 kg d^{-1} cow^{-1}. This result fell close to the OMAFRA (Ward and McKague 2015) typical average (25 kg d^{-1} cow^{-1}) for heifers in the 5 to 24 month age group. Based on average weights provided by the farmer (136 kg for 2-6 month heifers; 272 kg for 6-17 month heifers), this value is at the top end of the range specified by Adams and Sharpe (1995) for heifers 5-18 months (14 to 27 kg d^{-1} cow^{-1}). Holter and Urban's (1992) three-variable equation for dry cows (eqn 7), which is based on DMI, dry matter percentage and the percentage of crude protein in dry matter, provided the best estimate results at 17 kg d^{-1} cow^{-1}. The higher actual FWI was likely due to warm temperatures; the heifers were housed in a non-air conditioned barn with daily maximum temperatures averaging 22.4ºC.

Based on the proposed water partitioning in the pasture, 10 dry cows consumed 415 kg d^{-1} cow^{-1} (8.6%) of the total farm FWI compared to 311 kg d^{-1} cow^{-1} (6.4.%) for

13 bred heifers. The 42 kg d^{-1} cow^{-1} intake assigned to pastured dry cows is the median of the range (34 to 49 kg d-1) provided by both OMAFRA (2007) and Adams and Sharpe (1995). It was considered a reasonable estimate falling between the 45 kg d^{-1} estimate used by van der Gulik et al. (2013) in British Columbia's AWDM and the 33 kg d^{-1} average suggested by Amaral-Phillips et al. (N.D.). In comparison to the lower end estimate presented by Amaral-Phillips et al., the higher intake value noted in the present study is justified by the amount of dietary CP introduced through pasture consumption. Appuhamy et al. 2015 noted that FWI rose from 4 to 8 kg d^{-1} when the percentage of crude protein in the diet increased from 15.2% to 18.5%. Interestingly, Holter and Urban's three-variable model for dry cows (eqn 7), which takes crude protein into consideration, under-estimated FWI by 11.95 kg d^{-1} cow^{-1}. This result reflected the difference in DMI, dry matter percentage and the crude protein percentage in dry matter in this study relative to the values used in Holter and Urbans's study. The modified Kertz equation (eqn 10) for lactating cows introduced by Adams and Sharpe (1995), however, provided a close estimate of 47 kg d^{-1}. Without consideration to milk output, this equation was strictly dependent on DMI and RWI.

The 24 kg d^{-1} cow^{-1} estimate for bred heifers (17 to 24 months) in the pasture is the difference between total metered pasture intake and dry cow intake. The value compares closely to the median (25 kg d^{-1}) of the OMAFRA (Ward and McKague 2015) estimated range of 14 to 36 kg d^{-1}; but, intake may be slightly under-estimated as this range applies to heifers in the 5 to 24 months age group. The value also fell slightly short of the Adams and Sharpe (1995) low end estimate of 28 k d^{-1} cow^{-1} for heifers 18 to 24 months. In considering the equations, however, the Urban and Holter (1992) three-variable model, (eqn 7), provided a similar estimate of 24 kg d^{-1} cow^{-1} lending credence to the accuracy of the study value.

The FWI for dry cows and heifers (2 to 17 and 17 to 24 months) located in the back barn during the cool season was not partitioned (Table 17). The cattle population in the back barn grew from 16 young heifers in the thermoneutral period to 33 animals in the cool period: 4 dry cows, 12 bred heifers (17-24 months) and 19 young heifers (2-17 months); yet, the total metered back barn consumption increased by only 37 kg d^{-1} cow^{-1} to 394 kg d^{-1} cow^{-1}. The total available water for the three groups declined from 10,485 kg for the 10-d thermoneutral period (back barn and pasture) to 3,944 kg for the 10-d cool period, a reduction of 6,541.1 kg (63.6%). In terms of the total farm FWI, the three groups accounted for 22.4% of FWI during the thermoneutral period but only 11.2% during the cool season. An attempt to partition the total metered water measurement was made using equations for dry cows and heifers FWI. Based on the lowest equation results, FWI allotment would be 29 kg d^{-1} cow^{-1} (eqn 17), 14 kg d^{-1} cow^{-1} (eqn 11) and 5 kg d^{-1} cow^{-1} (eqn 11) for dry cows, bred heifers and young heifers respectively. With the recorded number of animals in each life-stage, the total water requirements at these intake levels (537 kg d^{-1}) would exceed the measured available water by 143 kg d^{-1}. Additionally, the intake values for both classes of heifers under this scenario were believed to be too low. Although colder temperatures are linked with decreased FWI, cattle continue to require adequate amounts of water during cooler temperatures; limiting water effectively limits feed intake and hinders the animal's ability to meet energy requirements (NRC-US 1981; Tarr 2010). The minimum water requirement for beef heifers below 4ºC is 15 kg d^{-1} cow^{-1} with amounts increasing with weight (NRC-US

1992). Based on a FWI of 15 kg d^{-1} cow^{-1}, which is also the low end of OMAFRA heifer FWI estimates (Ward and McKague 2015), cool period FWI requirements for heifers (2-24 months) alone would be 465 kg d^{-1}; a value already exceeding the metered back barn water count without consideration of dry cow needs. As a result of the inability to accurately divide water-use relative to equation estimates and established standards, final partitioning values for the back barn cool period have not been included in this study.

Overall, the measured and partitioned data for the thermoneutral period and the FWI for lactating cows in the cool period provided a highly reliable set of values for the study site. With the exception of temperature and humidity, the measured quantities from Site A3 were analyzed without consideration of environmental or management impacts; yet, they closely reflect the values found in literature. With regard to equation results, the moderate over and under-estimation of the study site FWI was not unexpected. With the high degree of variables which may impact water intake between farms, (i.e. cattle characteristics, temperature, humidity, radiation, diet composition, milk production, and water temperature as noted in Section 2.5.1), equation estimates will vary.

4.4.3. Cattle Ration Water Intake (RWI)

Calculations of RWI (eqn 15) (Table 18 and 19) were added to measured FWI to determine the total water intake for each life-stage (Table 17). For lactating cows, RWI accounted for 9.5 % and 13.8% of the total water intake during the thermoneutral and cool period respectively; the contribution of feed moisture to total water intake for both periods fell within the typical reported range of 10 to 20% (Beede 2005; Harner et al.2013). Alfalfa (64.7%) supplemented by pasture (22.7%) accounted for the majority of the thermoneutral RWI while cool season RWI was contributed to by alfalfa (54.6%), corn silage (26.2%) and high moisture corn (17%). While the quantity of alfalfa intake remained constant in both periods, the added corn grain intake in the cool period can be attributed to increased wintertime energy needs (Tarr 2010). The only notable difference in average diet characteristics for lactating cattle between this study at Morewood and those by Appuhamy et al. (2014) and Khelil-Arfa et al. (2012) (description of studies in Appendix F) was the crude protein content which was higher that the 16.4 = 16.5% noted in those studies.

For young heifers in the thermoneutral period, RWI was responsible for 10% of total water intake with alfalfa accounting for 88.7% of the feed moisture. Alfalfa again dominated the cool season RWI (61.1%); but, corn silage also made a notable contribution (30.6%). The impact of RWI on the total water intake of dry cows and bred heifers in the thermoneutral period was 47.8% and 51.2% respectively (Table 17). This may be attributed to diet composition with pasture (75% moisture content) accounting for 92.6% of the dry cow diet and 89.8% of the bred heifer diet. In the cool season, corn silage intake by dry cows and bred heifers was two times that of lactating cows and accounted for 79% of their RWI. In considering the combined seasonal diets of dry cows and bred heifers, it is noted that the overall DMI decreased significantly from 26 kg d^{-1} in the thermoneutral period to 10.5 kg d^{-1} in the cool period. This is an anomaly in that cattle, as previously noted, increase feed consumption in cold temperatures to generate body heat (Tarr 2010). Plausible explanations for this anomaly include: an over-estimation of pasture intake as calculations were based on DMD estimations which relied on a static average body weights or, in spite of conferring with the farmer, an under-estimation of the alfalfa ration for dry cows and bred heifers.

Table 18 Cattle dietary inputs for the Morewood, Ontario, study site (A3) for the September 25 to October 4, 2014 (DOY 268-277) thermoneutral period.

	Daily Ration* (kg d^{-1})	Moisture Content* %	Dry Matter %	CP* % of DM	CP Intake (kg d^{-1})	N [2] Intake (kg d^{-1})	Ration Water Intake (RWI) (kg d^{-1})	Dry Matter Intake (DMI) (kg d^{-1})
Milking Barn (33 Lactating Cows at 680 kg cow^{-1})[1]								
Alfalfa/ Grass	22.0	35	65	25	5.5	0.9	7.7	14.3
HMC**	5.4	26	74	12	0.6	0.1	1.4	4.0
Soybean	1.4	13	87	19	0.3	0.05	0.1	1.2
Pasture	3.6	75[3]	25	16	0.6	0.1	2.7	0.9
Total	32.4				7	1.1	11.9	20.4[4]
Back Barn (5 Heifers 2 to 6 months at 136 kg cow^{-1} / 11 Heifers 6 to 17 months at 272 kg cow^{-1})								
Alfalfa/ Grass	6.3	35	65	25	1.6	0.3	2.19	4.1
HMC	0.9	26	74	12	0.1	0.02	0.23	0.7
Soybean	0.5	13	87	19	0.1	0.02	0.05	0.4
Total	7.6				1.8	0.3	2.47	5.1
Pasture (10 Dry Cows at 816 kg cow^{-1} / 13 Bred Heifers Over 17 months at 454 kg cow^{-1})								
Dry Cows								
Alfalfa	3.9	35	65	25	1.0	0.2	1.4	2.5
Pasture	48.6	75	25	16	7.8	1.2	36.4	12.2
Dry Total	52.5				8.8	1.4	37.8	14.7[4]
Bred Heifers								
Alfalfa	3.9	35	65	25	1.0	0.2	1.4	2.6
Pasture	35.1	75	25	16	5.6	.9	26.3	8.8
Heifer Total	39.1				6.6	1.1	27.7	11.3[4]
Pasture Total (Dry Cow and Bred Heifer)					15.4	2.5	65.5	26.0

*Daily ration, moisture content, CP (crude protein) % data for non-pasture intake provided by farmer.

**HMC = High Moisture Corn

[1] Calf diet excluded in total (FWI 18 kg d^{-1} + RWI (4 kg of milk X .87) = 21.5 kg d^{-1})
Limited water content of daily calf starter not included in estimate

[2] Nintake (kg d^{-1}) = Crude Protein / 6.25

[3] Pasture Moisture level determined from USDA-NOP (2011)

[4] Dry Matter Demand used to assess kg of pasture consumed. DMD (eqn 30a)
Lactating Cows (1500 lb x (3.0/100) = 45 lbs = 20.41 kg
Dry cows (1800 lb x (1.8/100) = 32.4 lbs = 14.7 kg
Bred Heifers (1000 lb x (2.5/100) = 25 lb= 11.34 kg

Table 19 Cattle dietary inputs for the Morewood, Ontario, study site (A3) for the February 13 to February 22, 2015 (DOY 44-53) cool period.

	Daily Ration* ($kg\ d^{-1}$)	Moisture Content* %	Dry Matter %	CP* % of DM	CP Intake ($kg\ d^{-1}$)	N^2 Intake ($kg\ d^{-1}$)	Ration Water Intake (RWI) ($kg\ d^{-1}$)	Dry Matter Intake (DMI) ($kg\ d^{-1}$)
Milking Barn (35 Lactating Cows at 680 kg cow^{-1})[1]								
Alfalfa/ Grass	22.0	35	65	25	5.5	0.9	7.7	14.3
HMC**	9.1	26	74	12	1	0.2	2.4	6.7
Corn Silage	6.8	55	45	9	0.6	0.1	3.7	3.1
Soybean	2.3	13	87	19	0.4	0.06	0.3	2.0
Total	40.2				7.5	1.3	14.1	26.1
Back Barn (4 Dry Cows at 816 kg cow^{-1} / 12 Heifers 17-24 months at 454 kg cow^{-1} / 7 Heifers 6-17 months at 272 kg cow^{-1} / 12 Heifers 2 to 6 months at 136 kg cow^{-1})								
Dry Cows/Heifers (17 to 24 months)								
Alfalfa/ Grass	4.3	35	65	25	1	0.2	1.5	1.1
HMC**	1.4	26	74	12	0.2	0.03	0.4	1.0
Corn Silage	13.6	55	45	9	1	0.2	7.5	6.1
Soybean	0.7	13	87	19	0.1	0.02	0.1	0.6
Total	20.0				2.3	0.5	9.5	10.5
Heifers (2 to 17 months)								
Alfalfa/ Grass	6.3	35	65	25	1.6	0.3	2.2	4.1
HMC**	0.9	26	74	12	0.1	0.02	0.2	0.7
Corn Silage	2.0	55	45	9	0.2	0.03	1.1	0.9
Soybean	0.5	13	87	19	0.1	0.02	0.1	0.4
Total	9.6				2.	0.4	3.6	6.0

*Daily ration, moisture content, CP (crude protein) % data provided by farmer
**HMC High Moisture Corn
[1] Calf diet excluded in total (FWI 18 kg d^{-1} + RWI (4 kg of milk X .87) = 21.5 kg d^{-1})
Limited water content of daily calf starter not included in estimate
[2]Nintake ($kg\ d^{-1}$) = Crude Protein / 6.25

4.4.4. *Cattle Water Outputs*

Milk production is noted in Table 20. The yield results fell below the regional average output of 30 kg d^{-1} (DFO 2013b; 2014) at 28.5 kg d^{-1} for the thermoneutral and 26.5 kg d^{-1} for the cool period. However, the EGLHLE average included production from all milk management systems. Tie stall milking systems tend to under-produce relative to free-stall systems as noted in a recent study of 17 Ontario farms (Robinson 2015) in which the average milk production from August 2013 to December 2014 for 6 farms employing a tie stall milk system was 27.2 kg d^{-1} compared to 32.3 kg d^{-1} for 11 free stall farms employing robotic, parlour, parallel or rotary milking systems.

The slight 0.1% increase in milk fat in the cool season (Table 20) reflected seasonal changes in diet and is indicative of normal trends in the EGLHLE; the fat content average reflected the 2013/2014 Ontario weighted average of 4.1% while the protein content (3.1/3.2%) was slightly below the Ontario weighted average of 3.3% (DFO 2014). Milk water-content followed seasonal milk production, decreasing by 1.7 kg d^{-1} in the cool period.

Table 20 Summary of milk yield and characteristics for the Morewood, Ontario, study site (A3) for the September 25 to October 4, 2014 (DOY 268-277) thermoneutral period and February 13 to February 22, 2015 (DOY 44-53) cool period.

Milk Production (cow-1)	Thermoneutral Period	Cool Period
Milk Yield (kg d^{-1})	28.5	26.5
Milk Fat Content %	4.1	4.2
Milk Fat (kg d^{-1})	1.16	1.1
Milk Protein Content %	3.1	3.2
4% Fat Corrected Milk (FCM) (kg d^{-1}) [1]	28.9	27.1
4% Fat and 3.3% Protein Corrected Milk (FPCM) (kg d^{-1}) [2]	28.46	26.9
Milk Water Content (kg d^{-1})	24.8	23.1

[1] FCM = (0.4 × my) + (15 × milk fat in kg d^{-1}) (McGill ND)
[2] Eqn 38 FPCM = milk yield (kg) × (0.337 + 0.116 × fat content (%) + 0.06 × protein content (%)) (FAO 2010)

4.4.5. Barn Water Inputs and Outputs

Besides drinking water, water inputs to the barn were primarily washwater. Washwater use varied from 673 kg d^{-1} in the thermoneutral period to 1005 kg d^{-1} in the cold period.[1] Based on a population of 33 lactating cows, water-use in the thermoneutral period water-use was 20 kg d^{-1} cow^{-1}. This value fell well below the maximum water-use limit of 64 kg d^{-1} cow^{-1} estimated by the OMAFRA Nutrient Management planning software (2015) for tie stall farms. Robinson (2015) reported similar values in an Ontario-based study of milkhouse washwater use with two farms in New Liskeard, Ontario, using 26 and 18 kg d^{-1} cow^{-1} and two farms in the EGLHLE using 21 and 18 kg d^{-1} cow^{-1}. The difference between the actual daily thermoneutral usage and the Nutrient Management software maximum may be attributed to the absence of a plate cooler at the farm; plate coolers use an estimated 45 kg d^{-1} cow^{-1} (OMAFRA 2015). The daily thermoneutral period water-use total also corresponded to the 15-20 kg d^{-1} cow^{-1} static value used in the Quantis, AGECO and CIRAIG (2012) study and the 20 kg d^{-1} cow^{-1} value used for lactating cows in British Columbia's AWDM (van der Gulik et al. 2013).

Barn water outputs consisted of washwater, bedding and cattle waste, the latter of which was collected and recycled to the field. For bedding, the farmer reported weekly use of approximately 680 kg of farm-grown wheat bedding straw (~97 kg d^{-1}) which was supplemented, when required, with wood shavings. A moisture content of 12% was assumed based on producer input; this value closely reflected the 10% moisture content estimate provided by Biernbaum and Fogiel (2013). Bedding water output was calculated to be 12 kg d^{-1}.

4.5. WatBal-Dairy

Table 21 displays the WatBal-Dairy prototype results for input, output and change in storage parameters contributing to the field to farm-gate water balances.

4.5.1. Field Environment Water Balance

The water balance of the field and pasture environments consisted of inputs, outputs and storage related to pasture crops, barn feed and bedding crops (Table 21). Inputs included total growing season (green) precipitation calculated at the field level for each crop, and daily manure water (recycled blue) amendments in the corn and pasture fields. Although manure made an insignificant contribution to inputs in both the crop fields (0.22%) and the pasture (0.32%), it was included in WatBal-Dairy testing to illustrate the integrated farm-system water balance.

Table 21 WatBal-Dairy per diem water balance testing results for the Morewood, Ontario study site (A3) including water-use in the field (72.4 ha of crops), pasture (21.0 ha), and cattle environments (74 animals in pasture and confinement conditions), as well as barn servicing and cleaning.

	Inputs* ($kg\ d^{-1}$)				**Consumed Outputs* ($kg\ d^{-1}$)**			**Recycled Outputs* ($kg\ d^{-1}$)**	**Change in Storage* ($kg\ d^{-1}$)**
Field	Precipitation (Green) (All Fields – 72.4 ha)			1,073,922	ET ($kg\ d^{-1}$ for field area)	Corn silage (3.2 ha)	33,385	Water in Crops Recycled to Cattle Ration	Soil storage including leaching/ runoff
						HMC (10.2 ha)	111,110		
	Manure (Recycled from cattle)			2,401		Alfalfa (32.8 ha)	369,247		
						Soybean (12.1 ha)	119,044		
						Wheat (14.1 ha)	118,440		
	BALANCE – Field Crops (72.4 ha)			1,076,323	ET Field Crops (72.4 ha)		751,226	472	324,624
Pasture	Precipitation (Green) (21.0 ha)			298,258	ET	Pasture (21.0 ha)	208,619	Water in Crop Recycled to Cattle Ration	Soil storage including leaching/ runoff
	Manure (Recycled from cattle)			964					
	BALANCE – Pasture (21 ha)			299,222	ET Pasture (21.0 ha)		208,619	708	89,895
BALANCE Field Crop/Pasture Environments (93.4 ha)				1,375,545	Field Crop/Pasture Environments (93.4 ha)		959,845	1,180	414,519
Cattle Pasture / Barn		Free Water (Blue Well/creek)	Ration Water (Recycled from crops)	Total Water Intake	Respiratory/ Cutaneous Water		Milk Water	Manure Water Recycled to Field	Body water
	Lactating Cows (n=33)	3,995	394	4,389	1,530		818	2,041	0
	Dry Cows (n=10)	465 (P)	365 (P) 14 (S)	844	355			489	0
	Heifers (17-24) (n=13)	278 (P)	343 (P) 18 (S)	639	163			476	0
	Heifers (2-17) (n=16)	263	40	303	- 43			346	0
	Calves (0-2) (n=2)	18	7	25	11			14	0
	Total Cattle	5,020	1,181	6,200	2,016		818	3,365	0
	BALANCE Cattle Environment (Barn and Pasture)			6,200	2,835			3,365	0
Barn	Washwater (Blue Well)		milk lines	462	Wash-water	milk lines	462	0	0
			bulk tank	25		bulk tank	25		
			miscellaneous	132		miscellaneous	132		
	BALANCE Barn Environment			619			619		0
Integrated Farm Water Balance:			**INPUTS:**	1,382,364	OUTPUTS: 963,300			RECYCLED: 4,546	STORED: 414,519
			Green:	1,373,361					
			Blue:	9,004					

HMC - High Moisture Corn; P) – pasture intake; (S) supplemental feed *Minor variations in calculated totals and parameter values attributed to rounding of values in WatBal-Dairy
Crop evaporative loss (harvest moisture content minus feed moisture content) and water in bedding were considered insignificant (<2.0%) and not included in balance

Crop water-use (column 2 in Table 21) accounted for 69.8% of the total water inputs in the field environment with consumption divided between field crops (78.3%) and pasture (21.7%). For the annual crops, high moisture corn had the greatest water-use, followed by corn silage, soybean and spring wheat (10,893, 10,433, 9,838 and 8,400 kg ha^{-1} d^{-1}, respectively). For the perennial crop of alfalfa, ET was 11,258 kg ha^{-1} d^{-1}, only 364 kg ha^{-1} d^{-1} greater than the per ha water-use of high moisture corn. However, the total crop water-use of alfalfa (369,247 kg d^{-1}) was over 3-times that of the other crops based on the extent of the growing area (i.e. 32.8 of 72.4 ha). The pasture ET was 9,934 kg ha^{-1} d^{-1}, slightly higher than the per hectare ET for wheat and soybean, which may be attributed to the mixed leaf area composition of the pasture.

Based on the yield and ET testing values used in WatBal-Dairy, the total field environment WUE was 17.7 kg DM ha^{-1} mm^{-1} with pasture having the lowest (5.5 kg DM ha^{-1} mm^{-1}) and corn silage the highest (37.5 kg DM ha^{-1} mm^{-1}) WUE. A detailed analysis of the WUE is found in Appendix L.

Recycled outputs (column 3 in Table 21) consisted of water contained in crops that became ration water inputs in the cattle environment. The recycled water in the pasture environment, which represented the 6 month grazing period from mid-May to mid-October, accounted for 60.0% of the total recycled water compared to 40.0% from the field crops. Overall, the recycled feed crop water represented less than 1% of the total field environment inputs.

Water storage in the 93.4 ha field environment (column 4 in Table 21) included water potentially held in the soil, or lost through run-off and leaching. Of the total storage value (414,519 kg d^{-1}), field crops contributed 78.3% and pasture contributed 21.7% of water. From a balance perspective, storage accounted for 30.1% of the total field water inputs.

4.5.2. Cattle Environment Water Balance

Inputs in the cattle environment (Table 21) were comprised of FWI (81%) estimated using equations and RWI (19%) identified through farmer input and the dry matter demand-based (USDA 2010) estimation of pasture intake. FWI was from well or creek blue water sources while RWI was classified as green water. Lactating cows (n=33) were responsible for the largest percentage (70.8%) of the total 6,200 kg d^{-1} water input for all cattle with dry cows (n=10), bred heifers (17-24 months) (n=13), young heifers (2-17 months) (n=16) and calves (n=2) accounting for 13.6%, 10.3%, 4.9% and 0.4% respectively.

FWI equation estimates generally compared well to measurements during the thermoneutral period at Morewood farm (A3) (Table 22). The equations over-estimated total FWI for all cattle by 3.8% (192 kg d^{-1}); less than the actual daily FWI of two lactating cows (113 kg d^{-1} cow^{-1}) at the study site. An analysis of the equation results by cattle life stage is found in Appendix M.

Table 22 Comparison of measured free water intake from the Morewood, Ontario, study site (A3) from September 25 to October 4, 2014 (DOY 268-277) to thermoneutral period and free water intake equation estimates used in WatBal-Dairy prototype testing.

	Cattle #	Measured FWI (kg d^{-1})	Estimated FWI (kg d^{-1})	Difference in Measured and Estimated FWI (kg d^{-1})	Difference per Animal (kg d^{-1})	Percentage Change (%)
Lactating Cows	33	3725	3995	-270	-8.2	-6.7
Dry Cows	10	415	465[1]	-50	-5.0	-10.8
Heifers (17-24 mths)	13	311	278[2]	+33	+2.5	+10.8
Heifers (2-17 mths)	16	358	263[2]	+95	+5.9	+26.5
Calves	2	18[3]	18[3]	0	0	0
Total	74	4827	5020*	-192*		-3.8

[1] Estimated by Eqn 10 (Adams and Sharpe 1995)
[2] Estimated by Eqn 7 (Cardot at al. 2008)
[3] Based on OMAFRA estimate (Ward and McKague 2015)
* Minor discrepancy in totals due to rounding

Recycled outputs were solely comprised of manure water excretions and accounted for 54.3% of the total cattle water inputs. For lactating and dry cows, estimates were based on fecal water (eqn 18) and urine (eqn 21). Lactating cows accounted for 60.6 % and dry cows 14.5% of the total excretion value of 3365 kg d^{-1}. Eqn 25 was used to estimate all heifer excretions with bred heifers (17-24 months) producing 14.1% and young heifers (2-17 months) producing 10.3% of the total recycled output. Calves accounted for the remaining 0.4% of manure water production.

The assumption of no change in body water (Silanikove et al. 1997; Boudon et al. 2012) accommodated the calculation of the respiratory cutaneous water component of consumed outputs in the cattle environment water balance, i.e. with storage = 0, respiratory cutaneous water = total water inputs - (milk + manure water outputs) (Table 21). The irregularity noted in respiratory cutaneous water (-42.6 kg d^{-1}) for young heifers may be attributed to the under-estimation of FWI (Appendix M). When the actual FWI of 22 kg d^{-1} $cow^{-1}$was entered into WatBal-Dairy calculator, respiratory cutaneous water for young heifers increased to 52.3 kg d^{-1} cow^{-1}.

Respiratory cutaneous water accounted for 71.6% and milk production 28.4% of daily consumed outputs in the cattle environment (Table 21). When young heifers were excluded from calculations for respiratory cutaneous water loss, lactating cows were responsible for 74%, dry cows 17%, bred heifers 8% and calves <1% of the total consumption. Overall, respiratory cutaneous water explained 32.5% and milk production 13.2% of the total cattle water intake.

In addressing the cattle environment water balance at the animal level, total water inputs for lactating cows were partitioned as: 35.1%, 18.6% and 46.3 % for respiratory cutaneous water, milk water (based on study site milk production) and manure water respectively. Water intake was divided between respiratory cutaneous water and manure water as 42.1% and 57.9% for dry cows and 25.6% and 74.4% for bred heifers (17-24 months). Partitioning for young heifers was not possible due to the negative respiratory cutaneous water result. The respiratory cutaneous water percentage for lactating cows and dry cows were high relative to previously discussed results from studies by Appuhamy et al. (2015) and Holter and Urban (1992); yet, this may be reasonable as cattle water inputs and outputs vary with diet composition, feed and water intake, and environmental conditions such as temperature and humidity (Weiss and St-Pierre 2010). For example, in a study by Silanikove et al. (1997), respiratory cutaneous water accounted for 33.8% of total water intake in mean temperatures varying from 12 ºC night-time to 14.2 ºC daytime. And, Boudon et al. (2012), reported respiratory cutaneous water as 32.5% of total water intake for dry cows in a controlled temperature of 15 ºC. This latter figure rose to 43.7% to 49.1% of total water intake under a controlled temperature of 28 ºC with varying sodium intakes. The temperature in the present study was uncontrolled varying from a daily mean of 11.4 ºC to 19.1 ºC with an average daily high of 22.1ºC. Overall, in considering the WatBal-Dairy results in the cattle environment, there is generally high confidence in the equation outcomes. In viewing the young heifer results, however, it is apparent that the reliability of results will depend on the integrity of inputted data.

4.5.3. Barn Environment Water Balance

Inputs in the barn environment consisted strictly of washwater (619 kg d^{-1}) (Table 21), which originated from a well-source (blue water). Green water in bedding (10 kg d^{-1}) has not been included in WatBal-Dairy calculations as it made an insignificant contribution (1.5%) to total barn water inputs. Washwater was divided between the daily cleaning of milking lines (74.7%), the bulk tank (4.0%) and miscellaneous uses (21.3%) such as milk house cleaning, feed preparation and washroom use. The bulk tank cleaning quantity of 25 kg d^{-1} reflected cleaning on alternate days, i.e. 50 kg every two days. At the animal level, the estimated washwater consumption was 19 kg d^{-1} lactating cow^{-1}; this value compared well with the daily milkhouse water-use totals of 17.9, 18.3, 21.0 and 25.9 kg d^{-1} cow^{-1} measured at other tie stall farms in Ontario (Robinson 2015). Relative to the actual measured water-use at the study site, the OMAFRA Nutrient Management software-based equations in WatBal-Dairy under-estimated total daily washwater use by

54 kg d^{-1}. This difference was deemed insignificant, however, amounting to only 1.7 kg d^{-1} lactating cow^{-1}.

Washwater, which was disposed of through a septic system, accounted for the consumed outputs in the barn environment. With no recycling of washwater and insignificant bedding contributions, recycled outputs were nil. There was also no change in storage associated with the barn environment. As such, the water balance for the barn environment was simplified to inputs = consumed outputs (Table 21).

4.5.4. Integrated Field to Farm-Gate Water Balance

Table 23 displays the results of the integrated farm-system water balance (inputs = consumed outputs – recycled outputs – storage). The total inputs from all environments (1,382,364 kg d^{-1}) were distributed as 69.7% consumed water, 0.3% recycled outputs and 30% storage. Inputs were comprised of 99.3% green water (1,373,361 kg d^{-1}) from precipitation (99.6%) and feed RWI (0.4%), and 0.7% blue water (9,004 kg d^{-1}). Blue water input was divided into well and creek sourced FWI (55.7%), well-sourced washwater (6.9%) and manure water returning to the field environment (37.4%). Water-use for the complete field to farm gate dairy operations was assessed at 29,190.9 kg d^{-1} cow^{-1} based on 33 lactating cows.

Table 23 Summary of WatBal-Dairy results by environment with percentage partitioning of field to farm-gate water balance components for the Morewood, Ontario, study site (A3) noted in parenthesis.

Environment	Inputs* (kg d^{-1})	Consumed Outputs (kg d^{-1})	Recycled Outputs (kg d^{-1})	Change in Storage (kg d^{-1})
Field**	1,076,323 (77.9%)	751,226 (78%)	472 (10.4%)	324,624 (78.3%)
Pasture	299,222 (21.6%)	208,619 (21.6%)	708 (15.6%)	89,895 (21.7%)
Cattle	6,200 (>0.45%)	2,835 (0.3%)	3,365 (74.0%)	0
Barn	619 (>0.05%)	619 (>0.1%)	0	0
Total	1,382,364	963,300	4,546	414,519
Farm Water Balance (%)*		(69.7%)	(0.3%)	(30.0%)

*Inputs = Consumed Outputs – Recycled Outputs - Change in Storage
**Minor variations in percentage totals attributed to rounding of values

The farm-level water balance was dominated by crop and pasture growth with the two environments accounting for 99.5% of inputs (precipitation and manure), 99.6% of water consumption and 100% of storage at the farm-system level (Table 23). Feed production has been noted as the primary contributor to consumptive water-use in milk production; Mekonnen and Hoekstra (2010) estimated that 98% of the WFP_{WFN} for animal products, including dairy, was attributed to feed production, while Zonderland-Thomassen and Ledgard (2012), in a study of a rain-fed farm in New Zealand, estimated the crop use amounted to 96.5% of the WFP_{WFN}. In considering the type of water, Sultana et al. (2014) and Mekonnen and Hoekstra (2010) estimated that green water accounted for 92.4% and 90.9% of the global dairy WFP respectively. Based on rain-fed management in this study, green water-use in crop and pasture production accounted for 99.3% of inputs.

Water inputs and consumption in the cattle and barn environments appeared inconsequential to the farm water balance in comparison to field and pasture contributions (Table 23); however, it is significant that the two environments combined for 100% (5639 kg d^{-1}) of the direct blue water inputs into the farm system. This total exceeded the average total blue water-use (drinking and milkhouse washwater) noted for Ontario tie stall farms of 4609.5 kg d^{-1} (Robinson 2015); however, the higher blue water inputs are deemed reasonable in view of a higher milk output (+10 kg d^{-1} cow^{-1}) at Morewood. In considering consumption, both the cattle environment at 0.3% and the barn environment at <0.1% of the total consumption fell below previous studies values which ranged from 1 to 11% for cattle intake (Mekonnen and Hoekstra 2010; Zonderland-Thomassen and Ledgard 2012; Sultana et al. 2014) and 0.8 to 8% for barn cleaning (Mekonnen and Hoekstra 2010; Sultana et al. 2014).

The lower net cattle water-use at Morewood (A3) was expected as recycling of manure water was not considered in other studies. Manure outputs in the cattle environment were responsible for 74% of the total farm recycled outputs and reduced actual blue water-use in the cattle and barn environment by 59.7%. The concept of recycling manure water within the farm is contrary to existing WFP and LCA methodologies (Mekonnen and Hoekstra 2010; Sultana et al. 2010; Quantis, AGECO and CIRAIG 2012; Hortenhuber et al.2012; Zonderland-Thomassen and Ledgard 2012), which consider urine and feces as water removed from and not returned to the catchment due to the change in water quality. In addressing the water balance, however, a strong argument can be made to support recycling and re-use within the same immediate environment.

From a product perspective, based on the 28.5 kg d^{-1} FPCM thermoneutral milk production average of 33 cows at Morewood, the WFP was 1025.7 kg H_2O kg^{-1} milk. This value fell above, but within reason, of the 940 to 948 kg H_2O kg^{-1} WFP results from other studies (Mekonnen and Hoekstra 2010; Hortenhuber et al. 2012; Zonderland-Thomassen and Ledgard 2012).

4.5.5. Assessment of Farm-System Water-Use Efficiency

Total farm water-use was heavily influenced by green water contributions (99.3%) and consumption in the field and pasture environments. Although rain-fed feed production is highly efficient in comparison to blue-water irrigated production (Quantis, AGECO CIRAIG 2012), improving green water-use efficiency remains a concern (NTREE 2010; Schreier and Wood 2013).

Improvement of water-use efficiency at the field and pasture level is influenced by limitations on crop selection, i.e. crops must ensure essential nutritional needs are being met to satisfy regulatory requirements and industry imposed expectations, and promote optimal milk production (NFACC/DFC 2009). The existing field crops at the study site were those best suited to prevailing agronomic conditions (OMAFRA 2014), and were selected and grown in quantities to satisfy the herd dietary requirements. Generally, the crops with higher WUE were those comprising most of the cattle diet, i.e. alfalfa and corn. Nevertheless, farm water-use may be reduced by improving the WUE of specific crops through the use of genetically superior crop varieties and/or improved agronomic management practices (Sadras et al. 2012).

Grazed pasture offers an attractive management consideration for dairy producers as it provides the cheapest source of nutrients and is less labour intensive than other feeding systems (Soder and Muller 2003). However, pastures are generally less water efficient than annual crops (Putman 2010; Moore 2005), and ensuring adequate and regular nutrient intake as required for consistent quality milk production is a major challenge (Soder and Muller 2003). At Morewood, grazing is a chosen management practice for feeding dry cows and heifers, and, to a lesser extent, lactating cows from mid-May through mid-October. As such, improving pasture WUE would significantly impact overall farm water-use efficiency. Enhanced pasture water productivity is generally achieved through rejuvenation with a fertilization program and controlled grazing, or through renovation with fertilization and reseeding with high-yielding forage species; the introduction of legume crops to pastures are particularly advantageous due to their longer root systems which promote greater WUE and their ability to fix nitrogen (Kyle 2015).

Blue water inputs in the cattle environment at Morewood appeared reasonable relevant to the noted level of milk production and the number of animals (Section 4.5.4). Measures may still be taken, however, to reduce water inputs. The use of nose pumps in the pasture environment and water bowls in the barns are both beneficial practices that have been associated with reduced water-use compared to troughs (Thompson et al. 2007). Replacement of the trough in the lactating cow yard with a nose-pumping system would undoubtedly contribute to lower FWI, with savings of perhaps 10-15% daily depending on existing waste and trough cleaning frequency (Harner et al. 2013).

Crude protein is positively correlated to water consumption (Murphy et al.1983; Khelil-Arfa et al. 2012; Appuhamy et al. 2015). At the study site, the quantity of crude protein in the diet of lactating cows, dry cows and bred heifers was high compared to other studies (Holter and Urban 1992; Khelil-Arfa et al. 2012; Appuhamy et al. 2014). It follows that decreasing crude protein intake at Morewood (A3) would improve water-use efficiency; however, this will require further assessment as the high crude protein intake is heavily influenced by intake of water-efficient alfalfa. It is possible that any water savings realized through lower crude protein intakes would be off-set through consumption of less water efficient crops.

Temperature is also a strong determinate of FWI with a strong positive correlation noted (Murphy et al. 1983; West 2003; Olkowski 2009). It is possible that the FWI for young heifers confined in the back barn may be decreased by reducing housing temperatures with improved ventilation. Further study would be required, however, to justify the expense.

Another potential method of improving water-use in the cattle environment is a reduction in the size of the replacement herd. By decreasing the number of bred heifers (17-24 months) and young heifers (2-17 months) by 10%, FWI would be reduced by 66.9 kg d^{-1}, and minor water savings would be realized in the reduction of non-pasture crops. However, implementing a reduction in replacement herd size will be largely influenced by the producer’s goals (herd size maintenance, upsizing or downsizing), the calving interval, age of first calving, calf mortality rates and culling rates for lactating cows (Kilmer and Tranel 2014).

With the introduction of robotic systems, cows generally average 2.5 daily milkings per cow (Nixon et al. 2009; de Koning 2010). Based on the existing milk production at Morewood of 28.5 kg d^{-1}, if milkings were increased to 3 times daily (production = 2.5), the number of lactating cows could be decreased from 33 to 26. This would result in a decrease in blue water FWI inputs of 847 kg d^{-1} and green RWI inputs of 82 kg d^{-1}. Pipeline cleaning and miscellaneous cleaning would increase by 231 kg d^{-1} and 66 kg d^{-1} with no change in bulk tank requirements; but, overall there would be a decrease in blue water inputs of 632 kg d^{-1}. Water-use would also be reduced through an anticipated decline in the required number of replacement cattle and, in the field environment, crop water-use would potentially be lower with the reduction in required feed. The water and potential cost savings, however, may not be feasible as introduction of a third milking would be time intensive and likely alter existing cattle feed patterns.

Water-use in the barn showed a high degree of efficiency reflecting the nature of the milk management system and equipment. As a tie-stall operation, water was not expended on parlour wash-down, resulting in a minimum savings of 3 kg d^{-1} cow^{-1} (99 kg d^{-1}). The savings increased to 17 kg d^{-1} cow^{-1} (561 kg d^{-1}) relative to parlour operations without recycling provisions. The absence of a plate cooler reduced water-use by another 45 kg d^{-1} cow^{-1} (1485 kg d^{-1}) while the absence of a water-based heat abatement system saved an additional 18.5 kg d^{-1} of use. As a small dairy farm, bulk tank cleaning occurred on alternate days subsequent to milk pick-up further reducing daily water-use relative to larger operations by 25 kg d^{-1}. To ensure continued efficiency of water-use in the barn environment, however, regular maintenance of the water systems is of utmost importance. As noted, a suspected leak in the Morewood water system resulted in a difference in measured washwater use of 332 kg d^{-1} between the thermoneutral and cool season.

4.5.6. WFP_{WFN} Calculation and Comparison

The transparency incorporated into the WatBal-Dairy 'results' tab accommodated the use of values from the calculator in WFP methodologies.

As noted in *The Water Footprint Assessment Manual* (Hoekstra et al. 2011), the WFP_{WFN} is an indicator of the freshwater volume from green and blue sources consumed through evaporation, incorporation into a product and/or polluted (grey water) per unit of time. For crops, WFP_{crop} is the sum of the green, blue and grey footprints (eqn 41) with the green and blue water footprints calculated as per eqn 42 and 43. Generally, the estimated crop water-use (ET in mm) is converted to m^3 ha^{-1} by applying a factor of 10 and yield is reported as ton ha^{-1}. Grey water is estimated as noted in eqn 44. For the barn WFP, the general process equation (45) is used. Water consumption is comprised of green (RWI) and blue (FWI) inputs into cattle and blue inputs in the barn system (pipelines, bulk tanks, parlour wash, milk and cattle cooling). The grey footprint has not been included in water-use calculations in this study.

(41) CROP WATER FOOTPRINT (WFPcrop) = WFgreen + WFblue + WFgrey

(42) WFgreen = Crop Water Use green / Harvested Yield (volume/mass)

(43) WFblue = Crop Water Use blue / Harvested Yield (volume/mass)

(44) WFgrey = L / Cmax - Cnat

where L is the pollutant load in mass/time; Cmax is the maximum acceptable concentration (ambient water quality standard) in mass/volume; Cnat is the natural concentration in the receiving water body in mass/volume.

The WFP_{WFN} results are compared to WatBal-Dairy results in Table 24; WFP_{WFN} results, which were calculated on an annual basis, have been re-calculated to daily use quantities to facilitate comparison. Although the method of estimating crop water-use differed between the WPF_{WFN} methodology and the WatBal-Dairy water balance framework, there was no difference noted in estimations of daily water-use at the field (field crops and pasture) level (959,846 kg H_2O d^{-1}). There were differences in the calculation of barn water-use (cattle and barn environments). The WFP_{WFN} calculated water consumption based on inputs of RWI, FWI and barn washwater as 6,820 kg d^{-1}; an increase of 3,366 kg d^{-1} relative to the WatBal-Dairy combined cattle and barn water-use consumption estimate (Table 24). The disparity in values was attributable to differences in theory; in WatBal-Dairy, consumption is equivalent to non-recycled outputs whereas the WFP_{WFN} relies on inputs with no consideration to recycling in green and blue water calculations. Recycling in the WFP_{WFN} would be reflected in a reduction of the grey WFP (Hoekstra et al. 2011).

Overall, the inclusion or exclusion of recycled water made little difference to farm-level consumption at the animal and product level. Based on 33 lactating cows, daily consumption differed by only 102 kg d^{-1} cow^{-1} and the WFP of milk by only 3kg H2O kg FPCM with the greater results in the WFP_{WFN} (Table 24).

In considering the use of the WatBal-Dairy results in other methodologies, it is apparent the framework is somewhat limiting in that it does not consider water-use along the supply chain and restricts calculation of indirect water-use to products that will impact the water balance; but, this does not preclude the addition of this information in the future. From a practical perspective, the framework is a valuable tool that is able to accommodate calculation in various methodologies of water-use that is directly pertinent to the dairy producer, i.e. water-use which is or may be impacted by the producer's management decisions and actions.

Table 24 Comparison of daily dairy water consumption results for the Morewood, Ontario, study site (A3) between the Water Footprint Network Water Footprint (WFP_{WFN}) and the WatBal-Dairy prototype calculator*.

	WFP_{WFN} Parameter	Water Consumption (kg yr^{-1})**	Water Consumption (kg d^{-1})	WatBal-Dairy Parameter	Water Consumption (kg d^{-1})
FIELD					
Green Water	Crop Water-Use (ET)	350,343,700	959,845	Crop Water-Use (ET)	959,845
Field Total Water Consumption		350,343,700	959,845		959,845
BARN (Cattle and Barn Environments)					
Green Water	Ration Water Intake	430,876	1,181	Respiratory Cutaneous Water	2,016
Blue Water	Free Water Intake	1,832,255	5,020	Milk Water	818
	Washwater	225,844	619	Washwater	619
Barn Total Water Consumption		2,488,974	6,820		3,454
INTEGRATED FARM					
Green Total		350,774,576	961,026		
Blue Total		2,058,098	5,639		
Consumptive Total		352,832,674	966,665		963,300
Water-Use per Cow (kg cow^{-1})		10,691,899	29,293		29,191
Water Footprint (kg_water/kg_FPCM)		1,029			1,026

*Minor variances in totals reflect rounding

** Annual consumption values reflect calculation with non-rounded daily consumption values from WatBal-Dairy

5. Summary and Conclusions

This study consisted of three distinct, yet integrated goals contributing to the development of a proto-type water-use quantification framework presented as an Excel calculator for Canadian dairy production. A summary of results relating to these goals follows:

5.1. DNDC Alfalfa Simulation

To support the use of DNDC for populating field and pasture environment parameters in WatBal-Dairy, the development of a regional growth algorithm for alfalfa is required. In this study, DNDC simulation results of ET, NEE, biomass and soil moisture were compared to measured data to identify short-comings in the existing alfalfa growth curve and biomass partitioning, and provide benchmarks for use in developing the Canadian-based regionalized algorithm.

DNDC over-estimated ET by 34.1% relative to *in situ* CPEC200 measurements with divergence between the simulation and measurement progressively increasing from early in the growing season. The over-estimation was particularly evident during the second-cut growth segment and extended into the autumn season as crop senesced and measured ET declined. With the overestimation in ET, soil moisture was underestimated although seasonal patterns were well represented. DNDC also over-estimated NEE (11.8%) on a seasonal basis relative to CPEC measurements. This was due to the simulation of continued biomass development after cuttings and during the period of senescence; but, DNDC also consistently under-estimated NEE during the maturation period of both first and second cuts. The DNDC biomass simulation result was slightly greater than *in situ* measurements from Site A1 primarily due to continued crop development after maturation and at the end of the season. Simulated WUE results were under-estimated largely due to the over-estimation of crop water-use as represented by ET.

Overall, DNDC results were influenced by climate variables, particularly temperature and, to a lesser extent, radiation. The failure of the model to represent changes in ET, NEE and biomass development in the post-cut period, and to recognize the change in the senescence period, may be attributed to an inappropriate growth curve and plant partitioning, which is indicative of the need for a regionally calibrated algorithm.

5.2. Identification and Evaluation of Water-Use Equations

Water-use measurements, particularly those from the thermoneutral period, generally corresponded to values in existing literature for tie stall farms, and provided a solid base for equation selection. The results for selected FWI equations varied from measured thermoneutral values by a minimum of -2.1 kg d^{-1} for bred heifers to a maximum of +8.2 kg d^{-1} for lactating cows with a total difference of 5.5 kg d^{-1} for all groups.

Equations for water-use in the barn environment were evaluated against *in situ* washwater use measured at the study site. Adaptation of the publically available Nutrient Management software program (OMAFRA 2015) was deemed the best-fit for WatBal-Dairy as the program provided a high degree of responsiveness and the estimated results were within 8% of the average measured water-use value. Calculations based on the

Nutrient Management software reflected the type of milking system, plate cooler water-use and recycling, cleaning cycle water-use and recycling, bulk tank cleaning, and allowed for miscellaneous water-use.

5.3. Development and Testing of the WatBal-Dairy Framework

The water balance concept formed the basis of the calculations in the WatBal-Dairy quantification framework and was presented in an Excel calculator. WatBal-Dairy results showed that the field and pasture environments dominated water-use at the study site accounting for 99.5% of inputs (precipitation and manure water), 99.6 % of consumed outputs and 100% of storage. Alfalfa was the biggest consumer with an estimated crop water-use of 11,258 kg ha^{-1} d^{-1}, followed by corn, pasture, soybean and spring wheat. Pasture had the lowest WUE at 5.5 kg DM ha^{-1} mm^{-1}.

Water consumption in the cattle environment, comprised of respiratory cutaneous water and water in milk, accounted for approximately 0.3% of total farm water-use. The largest part of cattle inputs (FWI and RWI) were accounted for in recycled outputs with water in manure being returned to the field environment. There was a discrepancy noted in the water balance for young heifers (2 to 17 months) indicative of the need to differentiate water and feed intake more precisely by weight. In this study, equal partitioning of intakes (FWI and RWI) was allocated to all heifers in the age group without regard to weight or stage of growth. Finally, there was minimal impact from barn water-use at the farm level with washwater inputs equalling outputs..

From an efficiency perspective, the farmer was already employing many water efficient practices in all environments. In the field, crop selection was consistent with prevailing conditions, yields satisfied the dietary needs of cattle without excess and the diet was concentrated on crops with greater WUE. With farm water-use being dominated by consumption of green inputs in the field and pasture environments, however, efforts to improve green WUE could potentially lead to greater water productivity, increased yields and reduced competition for water resources.

In the cattle environment, FWI was largely controlled by nose pumps and water bowls. Water-use in the barn during the thermoneutral period was highly efficient due to the management style (tie stall) and equipment. The absence of a plate cooler and water heat abatement system, and the cleaning of the bulk tank on alternate days, significantly reduced water consumption. Measurement results from the cool period suggested a potential leak in the milkhouse water line. Constant monitoring and maintenance of water lines is key to minimizing water waste.

The overall product (milk) WFP for the study site was 1026 kg H_2O kg FPCM milk^{-1}. When actual measured quantities were employed in the calculator for FWI and washwater, there was a difference in the WFP of only 0.2 kg H_2O kg FPCM, which suggests excellent overall precision in the selected equations. The calculator may be further strengthened with tie-ins to climate factors and more precise body weight data. Based on simple inputs, outputs and storage areas, WatBal-Dairy provides a suitable structure to ensure consistency in data collection, and the data may be easily transferred to other WFP methodologies where upstream and indirect water-use can be added.

5.4. Conclusions and Future Considerations

This study has shown that the water balance framework presented as the WatBal-Dairy prototype calculator shows great potential as a tool to provide the consistent, comparable measurement data required to assess water-use efficiency and inform decisions relevant to improved management practices in the Canadian dairy production. Further development of the calculator is required, however, to enhance the accuracy of water-use measurements and potentially enable use of the tool at the producer level.

In the field environment, further *in situ* studies are needed to calibrate and validate the DNDC alfalfa algorithms prior to incorporation in the practical framework. Additional *in situ* measurements are also required in the cattle environment to ensure equations accurately reflect cattle inputs and outputs by life-stage and weight under variable temperature and management conditions. The results of this study did not take into consideration cattle consumption in temperatures exceeding the upper thermoneutral boundary, i.e. >25^{o} C. It is known that cattle FWI will increase and DMI decrease in high temperature condition (McDowell and Weldy 1967; Murphy et al. 1983). Studies are required to ensure that equations accurately portray consumption in all temperature ranges. The linking of WatBal-Dairy to on-line climate data will also permit the use of equations providing greater flexibility and accuracy.

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Appendix A Gravimetric soil moisture content to volumetric soil moisture content calculation results from study site A1 – A4

Site	Date	Depth (cm)	Bulk Density (g cm^{-3})	Measured Gravimetric Water Fraction (%)	Gravimetric to Volumetric Water Fraction (%)	TDR Measured Volumetric Water Fraction (%)	Correlation Coefficient by Field
A1	16/06/2014	5	1.14	0.20	0.23	0.22	
		10	1.18	0.26	0.30	0.28	0.94
		20	1.59	0.18	0.28	0.31	
		30	1.05	0.32	0.33	0.33	
		50	1.25	0.30	0.37	0.39	
A1	23/09/2014	5	1.18	0.30	0.35	0.36	
		10	1.27	0.27	0.35	0.33	
		20	1.21	0.27	0.32	0.30	
		30	1.33	0.24	0.33	0.33	
		50	1.20	0.31	0.38	0.41	
A2	16/07/2014	5	1.34	0.29	0.39	0.36	
		10	1.35	0.27	0.37	0.33	0.88
		20	1.35	0.26	0.35	0.32	
		30	1.48	0.19	0.29	0.31	
		50	1.41	0.21	0.29	0.29	
A3	17/06/2014	5	1.14	0.27	0.31	0.29	
		10	1.25	0.27	0.34	0.33	0.82
		20	1.41	0.22	0.31	0.34	
		30	1.41	0.20	0.29	0.35	
		50	1.37	0.24	0.33	0.35	
A3	02/10/2014	5	1.32	0.21	0.28	0.20	
		10	1.31	0.23	0.30	0.26	
		20	1.42	0.24	0.34	0.35	
		30	1.12	0.35	0.39	0.40	
		50	1.43	0.17	0.24	0.22	
A4	17/06/2014	5	1.48	0.24	0.35	0.33	
		10	1.33	0.27	0.35	0.34	0.53
		20	1.28	0.28	0.35	0.33	
		30	1.20	0.23	0.28	0.43	
		50	1.30	0.20	0.26	0.36	
A4	02/10/2014	5	1.31	0.19	0.25	0.18	
		10	1.20	0.19	0.22	0.22	
		20	1.30	0.19	0.25	0.19	
		30	1.21	0.16	0.20	0.26	
		50	-	-	-	0.20	

Appendix B Operations of Campbell Scientific Instruments

CS616

The CS616 determines the volumetric water content of the soil from 0% to saturation as a function of dielectric permittivity calculated from each of the sensors by means of electro-magnetic pulses travelling between two prongs (CS 2012). Based on manufacturer's calibration, CS616 provides ±2.5% accuracy on volumetric water content readings when bulk density ≤ 1.55 g cm^{-3} and electrical conductivity is ≤ 0.5 dS m^{-1}.

HFT3

The HFT3 uses a series of thermopiles to measure temperature gradients of the upper soil surface area across the plate surface. Data sent from the sensors to the datalogger is manipulated by embedded software in conjunction with CS616 and TCAV thermocouple data to provide measurements of soil heat flux, heat capacity and the storage term. The plates are individually calibrated by the manufacturer and have a better than 5% accuracy reading (CS 2003).

TCAV-E/T

A TCAV-E Averaging Thermocouple consists of two pairs of probes joined at a central junction: each pair is comprised of a temperature reference and a temperature measurement probe that meet at a common point prior to connection to the central junction. Differences in temperature between the reference and measurement probes are reflected through changes in voltage potential and sent to the central junction where results are averaged (CS 2006). The TCAV-T is a standard single wire soil temperature sensor. Error levels with TCAV thermocouples are variable and are dependent on differences in ground potential between the datalogger and the measurement probes (CS 2015).

NR-LITE Net Radiometer

The NR-LITE provides measurements of net radiation, expressed as watts per square meter (W m^{-2}), by calculating the difference between outgoing energy received from the soil surface on the bottom sensor and incoming energy received by the up-facing sensor. The NR-LITE is sensitive to wind speed but when installed with a system where wind speed is measured, corrections can be applied resulting in highly accurate data (CS 2010).

Appendix C Summary of Processing Options Available in EddyPro, Options Applied to Raw Flux Data Obtained from the CPEC200 Installation at Site A1 and Rationale for Application

Processing Options in EddyPro		Processing Option Selected for CPEC200 Study Data with Description	Rationale for Selection
Raw Processing Options	Axis rotation for tilt correction	Double Rotation (Compensates for vertical misalignment of the anemometer)	Recommended when: - site is characterized by homogeneity, flatness and isotropy -soundly assumed wind streamlines are parallel to the surface - canopy height and roughness changes quickly as it does during the alfalfa growing season
	Detrending	Block Average (Retains largest amount of low frequency content)	Obeys the Reynolds decomposition rule (basis of eddy covariance method)
	Time lags compensation detection	Automatic time lag optimization (default time lags and plausibility windows are optimized as a function of relative humidity. This method will also optimize time lags for $CO_{2)}$	Most suitable for water vapor in typical closed path set ups
WPL Terms	Compensate Density Fluctuations	Convert high-frequency raw data from molar densities to mixing ratios (A priori correction to flux estimates)	Method developed by Burba et al. 2012 for closed path systems and recommended by LI-COR for systems such as CPEC200
Fast Fourier Transform	Tapering Window	Hamming (Tapering required to condition data before Fourier transform can be taken)	Method recommended by Kaimal and Kirstensen (1991)
Other Processing Options	Quality Check	Mauder and Foken (2004) – 0-1-2 system (Flagging of questionable or poor data generally outside of an acceptable threshold)	Selected for simplicity and compliance with international practices such as FLUXNET
	Footprint Estimation	Kljun et al. (2004) (Flux footprint formulations estimate location and relative importance of passive wind sources which influence flux measurements at a specified intake height. Footprint estimates vary in size, atmospheric stability and surface roughness.)	Uses a scaling method for flux footprint modeling over varying atmospheric conditions at various intake heights from near surface to middle of the boundary layer Method accounts for the influence of roughness length on the footprint and allows for quick processing.
Spectral Correction Options	Low Frequency Range	Moncrieff et al. (2004) (Analytic high frequency correction of high-pass filtering effects)	Recommended by LI-COR.
	High Frequency Range	Moncrieff et al. (1997) (Analytic high frequency spectral correction of low-pass filtering effects)	Fully analytic and allows for faster data processing.
Additional Processing			
		Dynamic crop height metadata file (Directs EddyPro to change crop height in processing algorithm)	Created metadata file to ensure crop heights were representative of actual field heights

Appendix D Sample of producer questionnaire used to determine farm practices at the Morewood, Ontario study site (A3).

Farm Name: _______________ Date: _____________

1. Crops and Pastures

Land Use					Fertilizer				Crop Management				Animal Feed	
Acreage	Crop or Forage Mix by Field	Rotation Cycle	Soil Type	Drainage (Y/N)	Fertilizer (e.g. manure/ chem)	Fertilizer Rate	Fertilizer Application Method	Fertilizer Timing	2014 Tillage Date	Plant Date	2014 Harvest Date(s)	2014 Yield	Moisture Content	% Used for Feed on Farm

2. Animal Management

			Calf	Heifer			Cow	
			0-60 Days	2-6 Mo	6-15 Mo	15-24 Mo	Lactating	Dry
Herd	Animal pop							
	Avg weight							
Feed	Feed quantity (kg DMI / day)							
	Feed composition Oct to May							
	June to Sept							
	Feeding frequency/ day	Mid-May to Mid-Oct						
		Mid-Oct to Mid-May						
	Type and % of feed obtained off-farm and location obtained							

Cow Breed(s):

Cows culled (number 2014):

Are numbers of animal types (calf, heifer, lactating, dry) consistent throughout the year (Y/N)?

If no, briefly explain variations:

Are feed composition and quantity consistent throughout the year (Y/N)?

If no, briefly explain variations:

3. Barn Management

BARN		BEDDING	
What is water source for barn (Well, creek, etc)?		**What type of bedding is used?**	
What is the cooling system for the barn? (natural ventilation, misting, etc)		**What quantity of bedding is supplied?**(i.e. kg/day)	
MILK TANK		**Where does bedding come from?** (on-site/ purchased)	
What type of cooling system is used for milk tanks?		**MANURE MANAGEMENT**	
Where does the water come from? (Recycled within system, from well, etc.)		**How is manure managed or collected?**	
HOW OFTEN ARE THE FOLLOWING CLEANED WITH WATER (Daily/times per day)		**Is any milking-system wash-water added to this manure storage?**	
Milking lines		**If not, where does it go?**	
Bulk tanks			
Milkhouse			
Water Bowls			
Water troughs			
Barn stalls / standing area			
Machinery (tractors, etc.)			

4. Animal Management and Milk Production by Month

(Please enter the number of animals and their location on farm by month)

2014-2015		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Calf Nursery (1-60 days)													
Heifer - Backbarn	2-6 mo												
	6-15 mo												
	15-24 mo												
Lactating Dairy Barn													
Dry Back Barn Pasture (May-Oct)													
Total Milk Production (L)													
Milk fat content (%)													
Protein Content (%)													
Offline treated animals													

Appendix E Summary of Quantitative and Required Result Parameters Initially Identified for Incorporation into WatBal-Dairy through Research and Consultation with AAFC Personnel and Dairy Producers

Appendix E(1) Potential Quantitative Parameters for WatBal-Dairy

Parameter	**Type of Flow/Requirement**
Field Parameter	
Precipitation	Direct input – total precipitation (rain, snow, hail)
Irrigation	Direct input – Total water from blue sources
Manure	Direct input – Total water incorporated in manure/ quantity of manure applied annually
Fertilizers	Direct/indirect input – Quantity of water in mix/total water incorporated in fertilizer
Pesticides / Fungicides	Direct/indirect input – Quantity of water in mix/total water incorporated in product
Transportation	*Indirect input – Total water incorporated in biofuels/distance traveled and fuel used*
Crop Use	Storage – Total water incorporated into plant/total ET and crop yield required
Soil Moisture	Storage – Total water held in soil available for crop use
Evapotranspiration	Output – Total of water evaporated from soil and transpired from crops
Surface Runoff	Output – Total of runoff water / % of pollutants
Percolation/Groundwater	Output – Total water moving laterally outside of root zone
Pasture Parameters	
Precipitation	Direct input – total precipitation (rain, snow, hail)
Irrigation	Direct input – Total water from blue sources
Manure	Direct input – Total water incorporated in manure/ quantity of manure applied annually
Fertilizers	Direct/indirect input – Quantity of water in mix/total water incorporated in fertilizer
Pesticides / Fungicides	Direct/indirect input – Quantity of water in mix/total water incorporated in product
Crop Use	Storage – Total water incorporated into plant/total ET and crop yield required
Soil Moisture	Storage – Total water held in soil available for crop use
Evapotranspiration	Output – Total of water evaporated from soil and transpired from crops
Surface Runoff	Output – Total of runoff water / % of pollutants
Percolation/Groundwater	Output – Total water moving laterally outside of root zone
Animal Water Intake	Direct Input – Total water consumed by cows, heifers, calves
Animal Feed (Pasture)	Direct Input - Water incorporated in pasture
Supplement Feed (While at pasture)	Direct/Indirect Input - Water incorporated in supplemental feed grown on site or purchased
Supplements	*Indirect Input – Water incorporated in supplements*
Animal Retention	*Storage – total water retained by animals for physiological use*
Dung/Uring	Output – Total dung and urine output from animals/ % of pollutants in water
Respiration	Output – Total water in respiration from animals
Animal Parameters	

Animal Water Intake	Direct Input – Total water consumed by cows, heifers, calves/number of animals
Animal Feed (Silage/Dry)	Direct Input - Water incorporated in feed grown on site
Animal Feed (Silage/Dry)	Indirect Input - Water incorporated in feed grown on site acquired off-site
Supplements	*Indirect Input – Water incorporated in supplements*
Animal Retention	*Storage – total water retained by animals for physiological use*
Dung/Uring	Output – Total dung and urine output from animals/ % of pollutants in water
Respiration	Output – Total water in respiration from animals
Milk Production	Output – Total milk produced per cow (average)
Barn Parameters	
Washwater Water	Direct Input/Output – Total water used for cleaning milking system, cooling tanks, animals, stalls, etc.
Cooling Systems (Milk)	Direct Input – Water used in pre-cooling/cooling tanks
Cooling System (Animals)	Direct Input – Water used for air conditioning/misting systems
Bedding	Direct Input/Output – Water incorporated in bedding grown on-site
Bedding	Indirect Input/Output – Water incorporated in bedding acquired off-site
Cleaning Products	*Water incorporated in cleaning products for tanks, milking systems, stalls, animals, etc.*
Transportation	*Indirect Input – Total water incorporated in biofuels*
Milk Spillage	*Output – Total water in milk lost during production process/quantity of milk*
Machinery	*Direct Input/Output – Cleaning/wheel ballast*

** Italicized entries excluded through scoping process*

Appendix E(2) Potential Result Parameters for WatBal-Dairy

Parameter	**Rationale**
Water-Use Efficiency	Required to access overall efficiency of water-use in field environment
Liters of Water/Liter of Milk	Overall assessment of farm water footprint
Total Green Water-Use	Required to ascertain partitioning of water-use
Total Blue Water-Use	Required to ascertain partitioning of water-use
Total Grey Water-Use	Required to ascertain partitioning of water-use

Appendix E(3) Farm details required for quantification of water-use

Location of Farm		
Crop and Field Details		
Crop Descriptors	Type of crop / size of field Planting date Harvesting date Crop use by % (feed, bedding, cash crop) Crop yield Moisture content	By field
Field Descriptors	Size of field (acres or hectares) Previous crop history (rotation) Soil type Drainage type	By crop
Tilling Practices	Type of management Dates of tilling	By crop/field
Fertilizer Use	Type - brand/manufacturer Chemical composition Quantity of water in mix Application quantity (rate of application) application dates Application method	By crop/field total
Insecticide /Fungicide Use	Type - brand/manufacturer Quantity of water in mix Total application quantity (rate of application) Application dates Application method	By crop/field total
Manure Use	Rate of application Application method Application timing Knowledge of composition	By crop/field total

Pasture and Grazing Details		
Pasture Characteristics	Size of pasture	
	Type of vegetation	Composition %
Grazing Characteristics	Number of animals	By type
	Grazing period	
Grazing Water	Type of water access	
	Quantity of water intake (if metered)	
Supplemental Feed	Type of feed	
	Quantity	By animal type
Supplements	Type - brand/manufacturer	
	Quantity	By animal type
	Frequency	
Animal and Feed Characteristics		
Cattle	Number by breed	Consistency of #
	Number lactating/ dry/ heifer cows by age groups	
	Number calves	
	Number veal calves	
	Number culled cows	
Cattle Weight By Type	Average weight lactating cows	
	Average weight dry cows	
	Average weight heifers (age groups)	
	Average weight calves	
	Average weight veal calves	
Milk Production	Average liters per cow	Quantity, fat, protein content
	Average fat content %	
	Average protein content %	
Feed	Composition of feed	By animal type
	Quantity of feed	
	Moisture %	
	Protein %	
	Timing of feeds	
	Type and quantity of purchased feed	Moisture %
Supplements	Type - brand/manufacturer	
	Quantity	By animal type
	Frequency	
Water Intake	Quantity by animal type (if metered)	

Barn Details		
Housing Style	Type by animal type (barn lay-out)	
Animal Cooling System	Type – brand/ manufacturer	
Method Of Drinking Water Access	Method of access / size of receptacle	
	Method of replenishing	
Type Of Milking System	Type and manufacturer	
Milk Cooling System	Type – brand/manufacturer	
Milk Spillage	Estimate of daily spillage	
Washwater	Frequency of line/bulk tank cleaning	
	Quantity (if metered)	
	Additional cleaning	Stalls/floors/machinery
	Cleaning products - type (brand/manufacturer)	
Bedding	Quantity and type of bedding used with moisture content	
Recycling	Nature of water recycling	
Manure Management	Type of system (solid/semi-liquid/liquid)	
	Method of storage	Covered/uncovered
	Method of dissolution of liquid waste	In solid systems

Appendix F - Results of scoping process as applied to the initial development of the WatBal-Dairy calculator

Goal/objective of study	To design a framework in the form of a calculator to determine field to farm-gate water-use on a dairy farm	
Boundaries	Water-use activity directly impacting the on-farm water balance as it related to milk production, i.e. no farm-house use	
Limitations	Input parameters must reflect reasonably accessible data for projected users; researchers (short-term) / dairy producers (long-term)	
Exclusions	Indirect water inputs (off-site processing)	No impact on farm-level water balance, (i.e. fertilizer, pesticides, supplements and bio-fuel production) Excludes products consumed by cattle plus bedding acquired off-site as use impacts farm water balance
	Hydro	Considered non-consumptive
	Machinery	Insignificant contribution
	Supplements	Insignificant contribution
Assumptions	Insignificant contribution	Activities or products that are reasonably expected to consume less than 2% or are proven to consume less than 2% of total water consumption are deemed to have an insignificant contribution and are excluded from calculations
	Uniform field coverage of single crop / uniform application of water inputs	No consideration given to the presence of other plants (i.e. grass, weeds) in field due to difficulty in assessing quantity No consideration of changes in yield within the same field. Changes may occur based on soil crusting, compaction, erosion, droughty or poor storage areas No consideration given to inconsistency in distribution of precipitation, irrigation, manure spreading or water-based chemical additives to the field

Appendix G Assumptions made relevant to the development of the WATBAL-Dairy calculator

ENVIRONMENT	ASSUMPTION	RATIONALE
Cattle	No metabolic water intake	Assumed negligible in comparison to free water and ration moisture intake (Beede 2005; Harner et al. 2013)
	No storage of water in animal	Assumed negligible (Silanikove 1997; Boudon et al. 2012)
Barn	Bedding inputs = outputs	Assumed that all bedding accounted for through manure or recycling
	No impact on manure output from evaporation or precipitation	Assumed negligible due to difficulty in estimating effect
	Spilt milk	Assumed to be an insignificant contribution

Appendix H Summary of Data Sources for Inputs Used in Testing of WatBal-Dairy

Field Environment		
Inputs	Growing Season Precipitation (mm)	AAFC data
	Irrigation (mm)	N/A
	Manure Water Content (mm)	Barn outputs x % moisture by type, (i.e. solid)
	Water-Use In Pesticide(s) (mm)	Farmer consultation
Outputs	Evapotranspiration (mm)	Estimates based on existing literature
	Evaporation from crops	Difference in harvest wet weight – Dry Matter weight
	Runoff (mm)	Water Balance (part of storage in prototype)
	Deep Percolation (mm)	Water Balance (part of storage in prototype)
Storage	Soil Moisture Content (mm)	Water Balance

Animal Environment		
Inputs	Free Water Intake (kg)	Equations
	Ration Moisture Content (kg)	Equation
	Dry Matter Intake	Farmer Consultation/Equation (Dry Matter Demand / Moisture Content)
Outputs	Feces Water	Equation
	Urine Water	Equation
	Respiratory Cutaneous Water	Equation
	Milk Water	Equation (Yield X.87)
Storage	Change in Body Water	Assumed = 0

Pasture Environment			
Inputs Field	-	Precipitation	AAFC
Cattle	-	Free Water Intake by Animal	Equation
Cattle	-	Ration Water Content (Pasture)	Farmer Consultation / Equation (Dry Matter Demand / Moisture Content)
Cattle	-	Ration Water Content (Supplemental Feed)	Farmer Consultation /Equation (Moisture Content)
Output Field	-	Evapotranspiration	Estimate based on existing literature
Field	-	Runoff	Water Balance (Storage)
Field	-	Percolation	Water Balance (Storage)
Cattle	-	Urine	Equation
Cattle	-	Feces	Equation
Cattle	-	Respiratory Cutaneous Water	Equation
Storage Field	-	Change in Soil Water	Water Balance (Storage)
Cattle	-	Change in Body Water	Assumed = 0

Barn Environment		
Inputs	Water in Feces	Equation
	Water in Urine	Equation
	Washwater	Nutrient Management Software Based Equation
	System Cooling Water	Nutrient Management Software Based Equation
	Animal Cooling Water	Harner et al. (2013) estimate
	Bedding Water	Farmer Consultation for Quantity /Moisture Content
Outputs	Water in Feces	Assumed = inputs
	Water in Urine	Assumed = inputs
	Moisture content in Bedding	Assumed = inputs
	Washwater	Assumed = inputs
	System Cooling Water	Assumed = inputs
Storage	Washwater	Assumed = inputs (Solid System only)*
	Animal Cooling Water	Assumed = inputs

* Washwater is not considered storage in a liquid manure system - recycled within farm system

Appendix I Literature Considered During Identification of Equations for Use in the WatBal-Dairy

Free Water Intake	Murphy et al. 1983	
	Holter and Urban 1992	
	Holter and Urban 1992	Based on Julian Day
	Cardot et al. 2008	
	Khelil-Arfa et al. 2012	
	Adams and Sharpe 1995	
	Appuhamy et al. 2014	Required feed analysis - ash
Dry Matter Intake	NRC-USA 2001	
	USDA-NOP 2011	
	Holter et al. 1997	Higher Comparable Standard Deviation > 8.7
	Robinson, PH 2011	
	McGill University N.D.	
Water in Milk	Appuhamy et al. 2014	
Fecal Water	Holter and Urban 1992	
	Khelil-Arfa et al.2012	
Urinary Water	ASAE 2005	Required nitrogen content of milk
	Khelil-Arfa et al. 2012	
	Nennich et al. 2005	Higher Comparable Standard Error 5.5 to 5.8
	Weiss 2004	
Total Manure Water	ASAE 2005	Required nitrogen content of milk
	Nennich et a.l 2005	Higher Comparable Residual Standard Error = 10.0 and 7.1
	Weiss 2004	
Dry Matter Excretions	ASAE 2005	
	Nennich et al. 2005	Higher Comparable Standard Error = 0.78, 1.21, 1.15
Respiratory Cutaneous Water	Silanikove et al. 1997	
Pasture Dry Matter Intake	Minson and McDonald 1987	
	USDA-NOP 2011	
	Muller 2004	Relied on Bite Size and Rate
	Holden 1993	Disappearance of Forage/Surgical/Markers

Appendix J Evaluation of Cattle Input and Output Equations with Rationale for Inclusion in WatBal-Dairy

Appendix J (1) Details of Evaluation and Selection of Cattle Input Equations (Free Water Intake and Dry Matter Intake)

FWI and DMI equations identified in Chapter 2 were vetted based on their ability to produce results reflecting the measured data from the study site and their practicality of use in the WatBal-Dairy calculator. Eqn 5, the National Research Council (NRC-USA) (2001) recommended equation, was discounted based on the practical accessibility to input requirements (sodium intake, minimum daily temperature). Table J (1a) provides a summary of FWI equation testing and evaluation results. Eqn 10 for lactating and dry cows and eqn 7 for all heifer groups were selected for use in WatBal-Dairy.

Rationale for FWI Equation Selection

For lactating cows, the modified Kertz equation (eqn 10 from Adams and Sharpe 1995) provided the closest thermoneutral estimate to measured barn and yard intake for lactating cows at 121.5 kg d^{-1}; an over-estimation of 8.6 kg d^{-1} . The other equations markedly under-estimated (-23.1 to -87.2 kg d^{-1}) or over-estimated (+17.9 to +128.4 kg d^{-1}) the actual FWI. In the cool period, eqn 10 significantly over-estimated FWI by 56.1 kg d^{-1}; a result attributed to a lower milk yield, a 5.7 kg d^{-1} increase in DMI and a 2.2 kg d^{-1} increase in respiratory cutaneous water. Eqn 6 (Murphy et al. 1983) provided the best estimate for the cool period with a 13.7 kg d^{-1} over-estimation. The discrepancy in the thermoneutral and cool period eqn 10 results is a matter for further study. Eqn 10 also provided the best estimate for dry cows with a 5.1 kg d^{-1} over-estimation of the measured

FWI value. Although created for lactating cows, by entering a nil value for the fat content of milk, the equation provided a FWI value based on DMI and respiratory cutaneous water. In comparison, the three-variable (DMI, dry matter and crude protein) eqn 7 created by Holter and Urban (1992) for dry cows resulted in an under-estimation of 12.4 kg d^{-1}.

Eqn 7, however, provided the best results for heifers with an under-estimation of 5.1 kg d^{-1} for heifers 2-17 months and 2.1 kg d^{-1} for heifers 17 – 24 months. The other equations, with the exception of eqn 11, were based on regression analysis relevant to lactating cows and over-estimated actual heifer FWI by 12.8 to 127.8 kg d^{-1} and 19.3 to 131.1 kg d^{-1} for heifers 2 to 17 months and 17 to 24 months respectively. Eqn 11 (Looper and Waldner 2002) also provided reasonable estimates; the results (-6.7 kg d^{-1}, heifers 2-17 months); (+11.7 kg d^{-1}, heifers 17-24 months) may have been closer to measured values with better attention to the variation in body weight within each age group.

Overall, eqn 10 and eqn 7 provided the best results in the thermoneutral period for the noted life-stages, and produced a very solid estimation of full-farm FWI of 206.3 kg d^{-1}; a difference of 5.5 kg d^{-1} or 2.7% from measured FWI.

Table J (1a) Results of free water intake equations with difference in equation results and actual free water intake measurements for the Morewood, Ontario study site (Site A3) September 25 to October 4, 2014 (DOY 268-277) thermoneutral period and February 13 to 22, 2015 (DOY 44-53) cool period noted in brackets.

	Actual Intake	Equation[1] 6 (kg d-1)	Equation[2] 7 (kg d-1)	Equation[3] 8 (kg d-1)	Equation[4] 9 (kg d-1)	Equation[5] 10 (kg d-1)	Equation[6] 11 (kg d-1)
Scope of Equation		Early Lactation	Dry	Mid-Lactation	Lactating/ Dry	Lactating	Heifers
Thermoneutral Period (September 25 to October 4, 2014)							
Lactating	112.9	89.8	50.0	130.8	241.3	121.5	25.7
		(-23.1)	(-62.9)	(+17.9)	(+128.4)	(+8.6)	(-87.2)
Heifer 2-17	22.4	35.2	16.5	73.1	150.2	43.7	11.3
		(+12.8)	(-5.9)	(+50.7)	(+127.8)	(+21.3)	(+11.1)
Dry Cow	41.5	58.0	29.1	52.9	178.5	46.5	30.9
		(+16.5)	(-12.4)	(+11.4)	(+137.0)	(+5.0)	(-10.6)
Heifer 17-24	24.0	50.0	21.4	48.5	155.0	43.2	17.2
		(+26.1)	(-2.6)	(+24.6)	(+131.1)	(+19.3)	(-6.7)
Cool Period (February 13 to 22, 2015)							
Lactating	88.4	102.1	63.56	120.51	257.20	144.54	25.70
		(+13.7)	(-24.8)	(+32.1)	(+168.8)	(+56.1)	(-62.7)

[1] Murphy et al. (1983); [2] Holter and Urban (1992); [3] Cardot et al. (2008); [4] Khelil-Arfa et al. (2012); [5] Adams and Sharpe (1995); [6] Looper and Waldner (2002)

Rationale for DMI Equation Selection

The USDA-NOP (2011) ‘as-fed’ equations (eqn 14 and 15), which are based on actual farmer inputs for feed intake quantities and either dry matter or moisture content percentages, were incorporated into WatBal-Dairy. As required elements in FWI and cattle output equations, inclusion of these equations enhanced the calculator’s overall accuracy while facilitating responsiveness. A secondary set of equations was also embedded in WatBal-Dairy in the event that the diet information is not available. The results of equation evaluation for these secondary models (eqn 12, 13 and 30) are noted in Table J (1b).

Eqn 13 provided the most accurate estimate of lactating cow DMI in the thermoneutral period with an over-estimation of 0.2 kg d^{-1} compared to an over-estimation of 4.2 kg d^{-1} for eqn 12. Conversely, in the cool period, eqn 12 provided a more accurate estimate with an under-estimation of 2.1 kg d^{-1} compared to 6.2 kg d^{-1} for eqn 13. The overall variance for both equations between the thermoneutral and cool period values was 6.3 kg d^{-1} and 6.4 kg d^{-1} for eqn 12 and eqn 13 respectively. Overall, however, eqn 13 was considered a more viable option as the required input variables (body weight and the fat content of milk) were better suited to WatBal-Dairy operations; eqn 12 relied on data relating to the fat content of milk, body weight and the specific week of lactation.

Eqn 12 and eqn 13 were deemed unsuitable for estimation of non-lactating DMI due to the milk related inputs required for calculations. Eqn 29 (Minson and McDonald 1987) for non-lactating cattle is dependent on body weight and average daily weight gain. Equations results were generated based on generalized farmer-supplied animal weights and an estimated daily weight gain of 0.9 kg d^{-1} for animals under 17 months and 0.8 kg d^{-1} for animals over 17 months as per Duplessis et al. (2015). Results for heifers in all weight classes were generally strong relative to the actual DMI, falling within a range of <1.9 kg d^{-1} to >1.2 kg d^{-1} for both the thermoneutral and cool periods. Eqn 29 results for dry cows showed the greatest variation relevant to actual intake with an under-estimation of 6.0 kg d^{-1} in the thermoneutral period and an over-estimation of 1.0 kg d^{-1} in the cool period. The thermoneutral under-estimation may point to an over-estimation of actual pasture intake as discussed in Section 4.4.3.

In considering all cattle groups, the farm measured DMI was 56.6 and 59.1 kg d^{-1} for the thermoneutral and cool periods respectively. In using eqn 13 for lactating cows and eqn 29 for other cattle groups, the thermoneutral farm result was under-estimated by 5.4 kg d^{-1} (10.5%) and the cool period 8.6 kg d^{-1} (17%). As most of the variance was attributed to a single factor in both periods, i.e., the under-estimation of dry cow DMI (6.2 kg d^{-1}) in the thermoneutral period and the under-estimation of lactating cow DMI (6.2 kg d^{-1}) in the cool period, there was a high degree of confidence in the noted equations that warranted their inclusion in WatBal-Dairy.

Table J (1b) Results of dry matter intake equations with difference in equation results and actual values for the Morewood, Ontario study site (Site A3) September 25 to October 4, 2014 (DOY 268-277) thermoneutral period and February 13 to 22, 2015 (DOY 44-53) cool period noted in brackets.

Scope of Equation	Actual DMI ($kg\ d^{-1}$)	Equation 12[1] ($kg\ d^{-1}$) Lactating	Equation 13[2] ($kg\ d^{-1}$) Lactating	Equation 30[3] ($kg\ d^{-1}$) Non-Lactating
Thermoneutral Period (September 25 to October 4, 2014)				
Lactating (680 kg)	20.4	24.6 (+4.2)	20.6 (+0.2)	
Heifer 2-6 (136 kg)	5.1			4.1 (-1.0)
Heifer 6-17 (272 kg)	5.1			6.3 (+1.2)
Dry Cow (816 kg)	14.7			8.7 (-6.0)
Heifer 17-24 (454 kg)	11.3			11.5 (+0.2)
Cool Period (February 13 to 22, 2015)				
Lactating (680 kg)	26.1	24 (-2.1)	19.9 (-6.2)	
Heifer 2-6 (136 kg)	6.0			4.1 (-1.9)
Heifer 6-17 (272 kg)	6.0			6.3 (+0.3)
Dry Cow (816 kg)	10.5			11.5 (+1.0)
Heifer 17-24 (454 kg)	10.5			8.7 (-1.8)

[1]NCR-USA (2001); [2] McGill University (N.D.); [3] Minson and McDonald (1987)

Appendix J (2) Details of studies used to identify cattle urine and fecal water (manure) estimates required for evaluation and identification of excretion equations to be used in WatBal-Dairy

Appuhamy et al. (2013)	Values based on the mean of urine and fecal water measurements taken from 315 lactating cows through the course of 50 energy balance trials at the former USDA Energy Metabolism Unit (EMU) (Wilkerson et al. 1997). The data was compiled by Appuhamy et al. (2013) for development (Set 1 n=670) and testing (Set 2 n=377) of a mechanistic model to quantify body water kinetics in lactating cows
Khelil-Arfa et al. (2012)	Provided estimates of urine and fecal water based on the mean of 342 measurements of FWI, RWI, urine and fecal outputs taken from 18 energy and nitrogen balance trials conducted at the Mejussaume experimental farm in France from 1983 to 2005
Weiss and St-Pierre (2010)	Estimated urine and fecal water outputs based on 315 observations of lactating cows from 15 experiments conducted at Ohio State University; the cows had an average milk yield of 31.2 kg d^{-1} and an average DMI of 21.9 kg d^{-1}. Heifer estimates based on measurements from other literature
Nennich et al. (2005)	Estimates based on mean excretion values from measured data extracted from published and unpublished experiments conducted at various American universities. Lactating cows had an average weight of 630 kg and an average milk yield of 31.4 kg d^{-1} (n= 554), dry cows (n= 18), heifers >250 kg (n=60) and heifers/calves < 50 kg (n= 46).
ASAE (2005)	Estimates developed from typical diets from 2002. The estimates were intended to be a rough approximation and did not consider body weight or milk yield.
Lorimor et al. (2001)	Estimates were calculated using diet-based formulas with data collected from a wide base of published and unpublished information. Body weight and milk yield were not considered in the estimate calculations.
USDA-NRCS (2008)	Estimate based on existing data sets and regression analysis that factored in milk production for lactating cows.
Nutrient Management Software Program (OMAFRA 2015)	Estimates taken from the Manure Storage (MSTOR) calculator within the Nutrient Management (NMAN) software program. MSTOR provides manure estimates based on animal life-stage, weight and milking or housing style. Estimates are rounded to the nearest tenth and include bedding materials. MSTOR is a tool provided to farmers to ascertain the best method of storing, treating and using manure (OMAFRA 2015).

Appendix J (3) Identification of fecal, urine and manure water estimates with rationale for estimates selected for use in evaluation of WatBal-Dairy cattle excretion equations

To assess the equations best suited for inclusion in WatBal-Dairy, it was necessary to identify values providing a reasonable estimate of excretions for the study site (A3).

Lactating Cattle

Fecal, urine and manure water estimates for lactating cows identified in the aforementioned documentation (Appendix J (2)) are noted in Table J (3a). For evaluation purposes, the identified values were partitioned using measured thermoneutral and cool period total water intake values and milk yields from the study site (A3). Partitioning refers to the breakdown of total water inputs into outputs by percentage and is based on the assumption that: (a) body water is constant--inputs equal outputs, and; (b) respiratory cutaneous water is the difference in the input/output balance as noted in eqn 28.

The final estimate values selected for evaluation of lactating cattle excretion equations were identified through a comparison of the output partition values noted in Table J (3a) to measured partition percentages from studies by Appuhamy et al. (2015) and Holter and Urban (1992). Appuhamy et al. (2015) provided a range for partitioning of thermoneutral outputs of 26.8% (±6.8%) for milk water, 21.6% (±10.7%) for respiratory cutaneous water, 28.1% (±5.7%) for fecal water and 23.5% (±6.8%) for urine (total manure 51.6 %). Outputs were based on measurements taken during a 3-d study of 12 Holstein cows with a mean total water intake of 103.1 kg d^{-1}, milk yield of 31.4 kg d^{-1} and DMI of 20 kg d^{-1}. The ambient temperature during the study was 25.9 ±1.4ºC. Holter and Urban's (1992) partition values were based on measured data from 329 lactating

Holsteins taken over a 6-d period. Cattle were housed in standard tie-stall barns in an ambient temperature of 18ºC. Study measurements (with standard deviations in brackets) were 90.2 kg d^{-1} (15.4 kg d^{-1}) for total water intake, 18.7 kg d^{-1} (2.8 kg d^{-1}) for DMI and 34.6 kg d^{-1} (6.8 kg d^{-1}) for milk production. Partitioning was recorded as 34% (5.4%) for milk, 18% for respiratory cutaneous water, 15% (3.9%) for urine and 33% (6.0%) for manure water.

The identified estimates for evaluation of lactating cow excretion equations were 23.0 kg d^{-1} for urine and 42.1 kg d^{-1} for fecal water (65.1 kg d^{-1} for manure) with resulting partitioning values for the thermoneutral period of 19.9% for milk water, 27.8% for respiratory cutaneous water, 18.5% for urine and 33.8% for fecal water (manure 52.3%). The values were based on the mean urine, fecal water and total manure measurement values provided by Lorimor et al. (2001), Nennich et al. (2005), and Weiss and St-Pierre (2010).

Table J (3a) Estimate results for lactating cattle outputs from existing studies and standards with partition percentages in brackets based on total water intake and milk water measurements for the Morewood, Ontario study site (Site A3) September 25 to October 4, 2014 (DOY 268-277) thermoneutral period and February 13 to 22, 2015 (DOY 44-53) cool period.

Study / Standard	Total Water Intake ($kg\ d^{-1}$)	Milk Yield ($kg\ d^{-1}$)	Average Weight (kg)	Milk Water ($kg\ d^{-1}$)	Respiratory Cutaneous ($kg\ d^{-1}$)	Urine [2] ($kg\ d^{-1}$)	Fecal Water [2] ($kg\ d^{-1}$)	Total [3] Manure ($kg\ d^{-1}$)	Manure Moisture (%)
Current Study	124.8 102.8	28.5 26.5	680	24.8 23.1	--	--	--	--	--
Appuhamy et al. (2013) Set 1			603	24.8 (19.9) 23.1 (22.5)	58.1 (46.5) 37.8 (36.8)	16.3 (13.1) 16.3 (15.9)	25.6 (20.5) 25.6 (24.9)	41.9 (33.6) 41.9 (40.8)	--
Appuhamy et al. (2013) Set 2			593	24.8 (19.9) 23.1 (22.5)	58.0 (46.4) 37.7 (36.7)	16.1 (12.9) 16.1 (15.6)	25.9 (20.8) 25.9 (25.2)	42.0 (33.7) 42.0 (40.8)	--
Khelil-Arfa et al. (2011)			630	24.8 (19.9) 23.1 (22.5)	46.2 (36.9) 25.9 (25.2)	21.2 (17.0) 21.2 (20.6)	32.6 (26.2) 32.6 (31.7)	53.8 (43.2) 53.8 (43.3)	--
Weiss and St-Pierre (2010)			--	24.8 (19.9) 23.1 (22.5)	37.0 (29.7) 16.7 (16.0)	23.8 (19.1) 23.8 (23.2)	39.2 (31.4) 39.2 38.1)	63.0 (50.5) 63.0 (61.3)	87.5
Nennich et al. (2005)			630	24.8 (19.9) 23.1 (22.5)	33.7 (26.9) 13.4 (13.0)	23.1(18.5) 23.1 (22.5)	43.2 (34.7) 43.2 (42.4)	66.3 (53.2) 66.3 (64.5)	~88
ASAE (2005)			--	24.8 (19.9) 23.1 (22.5)	40.9 (32.0) 20.6 (20.0)	*19.7 (15.8)* *19.7 (19.2)*	*39.4 (31.6)* *39.4 (38.3)*	59.1 (47.4) 59.1 (57.5)	87
Lorimor et al. (2001)			680	24.8 (19.9) 23.1 (22.5)	34.1 *(27.2)* 13.8 (13.4)	*22.0 (17.7)* *22.0 (21.4)*	*43.9 (35.2)* *43.9 (42.7)*	65.9 (52.9) 65.9 (64.1)	88
USDA-NRCS (2008)			624	24.8 (19.9) 23.1 (22.5)	44.5 (35.6) 24.2 (23.5)	*18.5 (14.8)* *18.5 (18.0)*	*37.0 (29.7)* *37.0 (36.0)*	55.5 (44.5) 55.5 (54.0)	87
NMAN* (2015)			680	24.8 (19.9) 23.1 (22.5)	48.5 (38.8) 28.2 (27.4)	*17.2 (13.8)* *17.2 (16.7)*	*34.3(27.5)* *34.3 (33.4)*	51.5 (41.3) 51.5 (50.1)	87.5

* NMAN - Nutrient Management Software Program (OMAFRA 2015)
[1] Upper value for thermoneutral period / lower value for cooler period with partitioning percentages of total water intake in brackets
[2] Italicized estimates based on 2:1 fecal water to urine ratio (Weiss and St-Pierre 2010)
[3] Total manure values after dry matter removed

Rationale for Selection of Estimate Values

Manure values from Nennich et al. (2005), Weiss and St-Pierre (2010), and the diet-based estimate from Lorimor et al. (2001) were highly comparable (within 3.3 kg d^{-1} (63.0 to 66.3 kg d-1) of each other) and fell within 2.7% (-1.1 to +1.6%) of the Appuhamy et al. (2013) mean manure partitioning percentage (51.6%) (Table J (3b)). The measured manure outputs from the Weiss and St-Pierre study best reflected the Appuhamy et al. partitioning percentages with total manure -1.1%, urine -4.4% and fecal water +3.3% off of the measured mean values. The fecal and urine values from the three studies also fell within or very close to one standard deviation of the fecal water and urine partitioning values attributed to Holter and Urban (1992). The 19.9% partitioning value for milk water that was (based on the Morewood (A3) total water intake) fell just below (0.1%) the low end of the proposed percentage range by Appuhamy et al. but notably below the 34% value indicated by Holter and Urban (1992). The variance in milk water production is indicative of the impact of environmental and management factors on cattle outputs (Lorimor et al. 2001; ASAE 2005). The respiratory cutaneous water percentage values averaged 6.3% higher than the Appuhamy et al. mean; but, fell within the proposed percentage range. In contrast, manure estimates from the Appuhamy et al. (2013) (Sets 1 and 2), Khelili-Arfa et al. (2012), USDA-NRCS (2008) and the Nutrient Management software (OMAFRA 2015) studies, resulted in respiratory cutaneous water partitioning percentages that exceeded the high end (32.3%) of the Appuhamy et al. (2015) partitioning range.

Table J (3b) Comparison of partitioning values for water outputs of lactating cows developed from published manure estimates and total water intake and milk yield measurements for the Morewood, Ontario, study site (A3) September 25 to October 4, 2014 (DOY 268-277) thermoneutral period to mean partitioning percentages and ranges for lactating cow outputs measured by Holter and Urban (1992) and Appuhamy et al. (2015)

Study Measurements:
Total Water Intake 124.8 kg d^{-1}
Milk Yield: 28.5 kg d^{-1}

	Milk Water (kg d^{-1})	Respiratory Cutaneous (kg d^{-1})	Urine [2] (kg d^{-1})	Fecal Water [2] (kg d^{-1})	Total [3] Manure (kg d^{-1})
Holter and Urban (1992)	34% (5.4)[4]	18%	15% (3.9)	33% (6.0)	48%
Appuhamy et al. (2015)	26.8% (20.-33.6%)[5]	21.6% (10.9-32.3%)	23.5% (16.7-30.3%)	28.1% (22.4 - 33.8%)	51.6%
Weiss and St-Pierre (2010)	24.8 (19.9%)	37.0 (29.7%)	23.8 (19.1%)	39.2 (31.4%)	63.0 (50.5%)
Nennich et al. (2005)	24.8 (19.9%)	33.7 (26.9%)	23.1(18.5%)	43.2 (34.7%)	66.3 (53.2%)
Lorimor et al. (2001)	24.8 (19.9%)	34.1 *(27.2%)*	*22.0 (17.7%)*	*43.9 (35.2%)*	65.9 (52.9%)

[1] Estimates of outputs followed by partitioning percentages of total water intake in brackets
[2] Italicized estimates based on 2:1 fecal water to urine ratio (Weiss and St-Pierre 2010)
[3] Total manure values after dry matter removed
[4] Under-scored values are standard deviations reported by Holter and Urban (1992)
[5] Estimated partitioning range as reported by Appuhamy et al. (2015)

Non-Lactating Cattle

The documentation review (Appendix J (2)) resulted in the identification of measurements and estimates for non-lactating cattle noted in Table J (3c). The identified output values were partitioned against measured thermoneutral total water intake from the study site. Although there is an absence of documented partitioning values for non-lactating cattle, the balance of the partitioning percentages accommodated a feasibility assessment of the proposed estimates.

Dry Cattle and Bred Heifers

The identified estimates for evaluation of dry cow excretion equations were 13.5 kg d^{-1} for urine and 24.5 kg d^{-1} for fecal water (38.0 kg d^{-1} for manure) with resulting partitioning percentages for the thermoneutral period of 52.1% for respiratory cutaneous water, 17.0% for urine and 30.9% for fecal water (manure 47.9%). Bred heifer (17-24 months) estimates were identified as 8.3 kg d^{-1} for urine and 16.0 kg d^{-1} for fecal water (24.3 kg d^{-1} for manure) with thermoneutral partitioning percentages of 52.9% for respiratory cutaneous water, 16.1% for urine and 31.0% for fecal water (manure 47.1%).

Rationale for Selection of Estimate Values

Urine, fecal water and manure estimates for dry cows and bred heifers were based on the mean of values from Lorimor et al. (2001), Nennich et al. (2005), and USDA-NRCS (2008). Manure values in the three studies showed a high degree of comparability with a difference of 0.1 kg d^{-1} for dry cows and 0.5 kg d^{-1} for heifers. In a study of measured data for dry, pregnant Holsteins (n= 60) by Holter and Urban (1992), partitioning of fecal water varied from 27 to 84.1% while urine varied by 12.4 to 42.3%.

Table J (3c) Estimate results for dry cow, heifer and calf outputs from existing studies and standards with partition percentages in brackets based on total water intake for the Morewood, Ontario, study site (A3) September 25 to October 4, 2014 (DOY 268-277) thermoneutral period [1]

Study /Standard	Total Water Intake ($kg\ d^{-1}$)	Average Weight (kg)	Respiratory Cutaneous ($kg\ d^{-1}$)	Urine[2] ($kg\ d^{-1}$)	Fecal[2] Water ($kg\ d^{-1}$)	Total[3] Manure ($kg\ d^{-1}$)	Manure Moisture (%)
Dry Cows							
Nennich et al. (2005)	79.3	755	40.7 (51.3)	15.4 (19.4)	23.2 (29.3)	38.6 (48.7)	~88
USDA-NRCS (2008)	79.3	755	40.7 (51.3)	*12.9 (16.3)*	*25.7 (32.4)*	38.6 (48.7)	87
Lorimor et al. (2001)	79.3	816	42.6 (53.7)	*12.2 (15.4)*	*24.5 (30.9)*	36.7 (46.3)	88
ASAE (2005)	79.3	755	46.3 (58.4)	*11.0 (13.9)*	*22.0 (27.7)*	33.0 (41.6)	87
Heifers (17-24 Months)							
Nennich et al. (2005)	51.6	437	27.1 (52.5)	9.0 (17.4)	15.5 (30.1)	24.5 (47.5)	83
USDA-NRCS (2008)	51.6	440	27.1 (52.5)	*8.2 (15.8)*	*16.3 (31.7)*	24.5 (47.5)	83
Lorimor et al.(2001)	51.6	454	27.6 (53.5)	*8.0 (15.5)*	*16.0 (31.0)*	24.0 (46.5)	88
ASAE (2005)	51.6	440	33.3 (64.5)	*6.1 (11.8)*	*12.2 (23.7)*	18.3 (35.5)	83
Heifers (2-17 Months)							
Lorimor et al. (2001)	24.9	272	10.5 (42.2)	*4.8 (19.3)*	*9.6 (38.5)*	14.4 (57.8)	88
USDA-NRCS (2008)	24.9	272	12.3 (49.4)	*4.2(16.9)*	*8.4 (33.7)*	12.6 (50.6)	83
Nennich et al. (2005)	24.9	153	12.5 (50.2)	4.1 (16.5)	8.3 (33.3)	12.4 (49.8)	~88
Weiss and St-Pierre (2010)	24.9	150	14.4 (57.8)	*3.5 (14.1)*	*7.0 (28.1)*	10.5 (42.2)	87.5
USDA-NRCS (2008)	24.9	136	14.8 (59.4)	*3.4(13.7)*	*6.7 (26.9)*	10.1 (40.6)	83
Calves (0-2 Months)							
ASAE (2005)	12.5	150	5.4 (43.2)	*2.4 (19.2)*	*4.7 (37.6)*	7.1 (56.8)	83
Lorimor et al.(2001)	12.5	113.4	4.5 (36.0)	*2.7 (21.6)*	*5.3 (42.4)*	8.0 (64.0)	88
USDA-NRCS (2008)	12.5	90	6.3 (50.4)	*2.1(16.8)*	*4.1 (32.8)*	6.2 (49.6)	83
NMAN (2015)*	12.5	90	3.7 (29.6)	*2.9 (23.2)*	*5.9 (47.2)*	8.8 (70.4)	87.5
Lorimor et al. (2001)	12.5	68	7.7 (61.6)	*1.6 (12.8)*	*3.2 (25.6)*	4.8 (38.4)	88

*NMAN - Nutrient Management Software Program (OMAFRA 2015)
[1] Partitioning percentages based on total water intake indicated in brackets
[2] Italicized estimates based on 2:1 fecal water to urine ratio (Weiss and St-Pierre 2010)
[3] Total manure values after dry matter removed

Young Heifers

Identified estimates (Table J (3c) for excretion equation evaluation for heifers reflected the variance in weight within the age group. The manure water estimate for 272 kg heifers (6-17 months) was 13.5 kg d^{-1} with an assumed 2:1 ratio of fecal water (9.0 kg d^{-1}) to urine (4.5 kg d^{-1}) applied to the estimate as per Weiss and St. Pierre (2010). Output partitioning percentages were calculated as 45.8% for respiratory cutaneous water, 18.1% for urine and 36.1% for fecal water (manure water 54.2%). The manure water estimate for 136 to 163 kg heifers (2-6 months) was 11.0 kg d^{-1}; divided as 3.7 kg d^{-1} urine and 7.3 kg d^{-1} fecal matter. Respiratory cutaneous water accounted for 55.8%, urine 14.9% and fecal water 29.3% (manure water 44.2%) of total water intake.

Rationale for Selection of Estimate Values

As indicated in Table J (3c), manure output estimates were positively correlated to cattle weight ranging from 14.4 kg d^{-1} for heifers weighing 272 kg to 10.1 kg d^{-1} for heifers weighing 136 kg. The variance reflected an increase in manure output of approximately 1.2 kg d^{-1} for every 45.4 kg (100 lb) of weight. To reflect the variance, estimates were based on the mean of values for cattle in their respective weight groups, i.e. the 272 kg estimate was based on values from Lorimar et al. (2005) and USDA-NCS (2008) while the 136 to 153 kg weight group was based on values from Nennich et al. (2005), the USDA-NRCS (2008), and Weiss and St. Pierre (2010).

Calves

Estimates from literature were highly variable with no definitive correlation to weight. In light of the variance, and the absence of equations for calf outputs in this study, the averaged value from all calf weight groups was used to produce a mean manure output estimate of 7.2 kg d^{-1}. This resulted in partitioning values of 57.6 % for manure and 42.4% for respiratory cutaneous water.

Appendix J (4) Details of Evaluation and Selection of Cattle Output Equations (Fecal Water, Urine and Manure Water)

Urine, fecal and manure water equations noted in Chapter 2 were evaluated against the identified output estimates to ascertain the best-fit formulas for the WatBal-Dairy calculator; both fecal/urine model combinations and single manure models were considered in the assessment. Note that while the estimates were based on thermoneutral conditions, they have been applied to both study periods for the purpose of evaluation. The results relative to the fecal water equations are noted in Table J (4a). Fecal water eqn 18 and urine eqn 21 were selected for inclusion in WatBal-Dairy for lactating and dry cows while eqn 25 was identified for heifers.

Rationale for Selection of Excretion Equations

Eqn 26 and eqn 27 (ASAE 2005) were not included in the evaluation as these s, which facilitated calculation of fecal water through determination of the actual dry matter content of both fecal and urine excretions, produced results significantly lower than the identified farm estimates.

Results from eqn 19 (Khelil-Arfa et al. 2012) were significantly biased with high over-estimations relative to the base estimates. Results were likely influenced by the high crude protein content in the cattle diet at the study farm. Eqn 18 (Holter and Urban 1992) is a relatively simple two-variable model based on DMI and dry matter content. Results for all animal classes were reasonable, falling within a range of -7.2 to +8.6 kg d^{-1} of the estimated output values. Although designed for calculation of fecal water in dry animals, it was notable that the equation provided the best result for lactating cows, under-estimating thermoneutral fecal water by 7.2 kg d^{-1} and over-estimating cool period fecal water by 0.4 kg d^{-1}. The equation also provided the best estimates for the pasture-based heifer group in the thermoneutral period (+5.6 kg d^{-1}) and dry cows in both study periods (+1.5 kg d^{-1} and -3.1 kg d^{-1}). Eqn 17 (Holter and Urban 1992) is a three-variable equation (DMI, dry matter % and milk yield) intended for lactating cows; yet, when a nil value was entered for milk, the equation provided the best estimate for young heifers (2-17 months) with under-estimations of 3.5 kg d^{-1} (136 kg) and 5.2 kg d^{-1} (272 kg) in the thermoneutral period and 0.4 kg d^{-1} (136 kg) and 2.1 kg d-1 (272 kg) in the cool period. The equation also provided the best estimate for heifers (454 kg) in the cool period with an over-estimation of 3.1 kg d^{-1}.

Table J (4a) Results of fecal water equations with difference in the equation results and mean estimate values developed from measurements and standards in existing literature noted in brackets.

	Estimated Fecal Water (kg d^{-1})	Equation 17[1] (kg d^{-1}) Lactating	Equation 18[1] (kg d^{-1}) Dry	Equation 19[2] (kg d^{-1}) Lactating/Dry
Thermoneutral Period				
Lactating	42.1	31.6 (-10.5)	34.9 (-7.2)	93.5 (+51.4)
Heifer 2-6 months (136 kg)	7.3	3.8 (-3.5)	14.9 (+7.6)	100.1 (+92.8)
Heifer 6-17 months (272 kg)	9.0	3.8 (-5.2)	14.9 (+5.9)	100.1 (+91.1)
Dry Cow	24.5	34.1 (+9.6)	26.0 (+1.5)	96.0 (+71.5)
Heifer 17-24 (454 kg)	16.0	26.6 (+10.6)	21.6 (+5.6)	97.4 (+81.4)
Cool Period				
Lactating	42.1	43.4 (+1.3)	42.5 (+0.4)	91.1 (+49.0)
Heifer 2-6 months (136 kg)	7.3	6.9 (-0.4)	15.9 (+8.6)	99.7 (+92.4)
Heifer 6-17 months (272 kg)	9.0	6.9 (-2.1)	15.9 (+6.9)	99.7 (+90.7)
Dry Cow	24.5	19.1 (-5.4)	21.4 (-3.1)	97.8 (+73.3)
Heifer 17-24 (454 kg)	16.0	19.1 (+3.1)	21.4 (+5.4)	97.8 (+81.8)

[1]Holter and Urban (1992); [2] Khelil-Arfa et al. (2012)

Results from the urine equations were highly variable as noted in Table J (4b). Eqn 20 (ASAE 2005), a simple equation designed to assess urine excretions from lactating cows based on body weight, over-estimated urine output by a minimum of 10.3 kg d^{-1} for all cattle groups with the exception of lactating cows. The result for lactating cows was highly significant with an over-estimation of just 0.3 kg d^{-1}. But, the overall value of the equation is questionable; with body weight as the only variable, changes in urine output associated with seasonal changes in diet are not reflected. Eqn 21 (Weiss

2004) provided the best cool period results relative to the assigned estimates for dry cows (-2.0 kg d^{-1}) and 454 kg heifers (+3.2); but, thermoneutral results showed a variance of 9.4 kg d^{-1} for dry cows and 12.2 kg d^{-1} for 454 kg heifers. Results for lactating cows showed less seasonal variance with over-estimations of 4.0 kg d^{-1} (thermoneutral) and 5.5 kg d^{-1} (cool). Equation results were dependent on quantities of DMI and the percentage of corn silage in the forage diet. Eqn 22 (Khelil-Arfa et al. 2012), which considers DMI and crude protein in forage and concentrates, provided the best thermoneutral period results for pastured animals (dry cows +5.4 kg d^{-1}; 454 kg heifers -5.4 kg d^{-1}) and over-estimated urine output for lactating cows by only 2.8 kg d^{-1}.Results for the cool period, however, were not as reliable with over-estimations of 14.4, 13.7 and 18.9 kg d^{-1} for lactating cows, dry cows and 454 kg heifers respectively. The higher cool period results reflect the additional crude protein in cattle diet; crude protein is strongly associated with increased urine output (Murphy 1992; Nennich et al. 2006; Khelil-Arfa 2012). None of the equations provided significant results for young heifers with over estimations for the 136 kg group of 10.3 to 14.3 kg d^{-1} and 8.3 to 10.7 kg d^{-1} for the thermoneutral and cool periods respectively. The consistent over-estimation suggests that the estimated evaluation values were low even though the estimate for the 136 kg group was influenced by measurement-based study results from Nennich et al. (2005) and Weiss and St-Pierre (2010). Results for the 272 kg heifer group showed similar over-estimations (11.5 to 13.5 kg d^{-1}; 7.5 to 11.8 kg d^{-1}).

Table J (4b) Results of urine excretion equations with difference in the equation results and mean estimate values developed from measurements and standards in existing literature noted in brackets.

	Estimated Urine Excretions (kg d^{-1})	Equation 20[1] (kg d^{-1}) Lactating	Equation 21[2] (kg d^{-1}) Lactating	Equation 22[3] (kg d^{-1}) Lactating / Dry
Thermoneutral Period				
Lactating	23.0	23.3 (+0.3)	27.0 (+4.0)	25.8 (+2.8)
Heifer 2-6 months (136 kg)	3.7	14.0 (+10.3)	16.0 (+12.3)	18.0) (+14.3)
Heifer 6-17 (272 kg)	4.5	16.3 (+11.8)	16.0 (+11.5)	18.0 (+13.5)
Dry Cow	13.5	25.6 (+12.1)	22.9 (+9.4)	18.9 (+5.4)
Heifer 17-24 (454 kg)	8.3	19.4 (+11.1)	20.5 (+12.2)	2.9 (-5.4)
Cool Period				
Lactating	23.0	23.3 (+0.3)	28.5 (+5.5)	37.4 (+14.4)
Heifer 2-17 months	3.7	14.0 (+10.3)	14.0 (+10.3)	12.0 (+8.3)
Heifer 6-17 (272 kg)	4.5	16.3 (+11.8)	14.0 (+9.5)	12.0 (+7.5)
Dry Cow	13.5	25.6 (+12.1)	11.5 (-2.0)	27.2 (+13.7)
Heifer 17-24	8.3	19.4 (+11.1)	11.5 (+3.2)	27.2 (+18.9)

[1] ASAE (2005); [2] Weiss (2004); [3] Khelil-Arfa et al. (2012)

Manure water estimate results are found in Table J (4c). Eqn 23 (Weiss 2004) was developed to predict manure excretion rates for lactating cows based on DMI and corn silage intake. The equation provided a solid result for lactating cows in the thermoneutral period (+3.7 kg d^{-1}); but, over-estimated the other cattle groups by a minimum of 9.5 kg d^{-1}. In the cool period, the equation is statistically the best for lactating cows (+19 kg d^{-1}), 136 kg heifers (+12.4 kg d^{-1}), and 454 kg heifers (+7.4 kg d^{-1}). Eqn 24 (ASAE 2005) is a dry cow equation limited in reliability by the single body weight variable. The equation produced high over-estimations for lactating cows and young heifers in both periods (> 13.8 kg d^{-1}); but, provided the most statistically significant results for dry cows (+1.8 kg d^{-1}) and 454 kg heifers (+7.5 kg d^{-1}). Eqn 25 (ASAE 2005) is a two-variable (DMI and body weight) regression model. Although developed for heifers, the equation provided the best thermoneutral period results for all groups other than 454 kg heifers. Cool period results for lactating cows and young heifers were not as accurate, generally reflecting the high estimates provided by eqn 23. In assessing the equation, it is evident that the results were influenced by the assigned partitioning of rations at the study site, particularly for the 136 kg and 272 kg heifers, i.e. the thermoneutral and cool period rations were equally partitioned to both weight classes resulting in a higher manure output for the smaller cattle (21.7 kg d^{-1} for 136 kg cattle vs. 17.7 kg d^{-1} for 272 kg cattle in thermoneutral; 25.2 for 136 kg cattle versus 21.2 kg d^{-1} for 272 kg cattle in the cool period). If the DMI was distributed to more accurately reflect the variance in weight, equation results would better reflect the estimates. This also applies to the allocation of feed to dry cows and 454 kg heifers in the cool period.

Table J (4c) Results of manure excretion equations with difference in the equation results and mean estimate values developed from measurements and standards in existing literature noted in brackets.

	Estimated Manure (kg d^{-1})	Equation 23[1] (kg d^{-1}) Lactating	Equation 24[2] (kg d^{-1}) Dry	Equation 25[2] (kg d^{-1}) Heifer
		Thermoneutral Period		
Lactating	65.1	68.8 (+3.7)	36.8 (-28.3)	65.3 (+0.2)
Heifer 2-6 months (136 kg)	11.0	23.0 (+12.0)	24.8 (+13.8)	21.7 (+10.7)
Heifer 6-17 months (272 kg)	13.5	23.0 (+9.5)	27.8 (+14.3)	17.7 (+4.2)
Dry Cow	38.0	51.7 (+13.7)	39.8 (+1.8)	39.4 (+1.4)
Heifer 17-24 (454 kg)	24.3	41.6 (+17.3)	31.8 (+7.5)	36.6 (+12.3)
		Cool Period		
Lactating	65.1	84.1 (+19.0)	36.8 (-28.3)	87.5 (+22.4)
Heifer 2-6 months (136 kg)	11.0	23.4 (+12.4)	24.8 (+13.8)	25.2 (+14.2)
Heifer 6-17 months (272 kg)	13.5	23.4 (+9.9)	27.8 (+14.3)	21.2 (+7.7)
Dry Cow	38.0	31.7 (-6.3)	39.8 (+1.8)	22.9 (-15.1)
Heifer 17-24 (454 kg)	24.3	31.7 (+7.4)	31.8 (+7.5)	34.4 (+10.1)

[1] Weiss (2004); [2] ASAE (2005)

While the comparison of equation results to the estimates provided important information, in determining the best equations for use in the WatBal-Dairy, consideration was also given to the partitioning of outputs relevant to the study site total water intake. The intent was to: (a) ensure a reasonable ratio of urine to fecal water outputs, and; (b) ensure a reasonable partitioning of respiratory cutaneous water relevant to percentages provided in existing literature.

Through the review of equation results and estimated output values, it was determined that lactating cows and dry cows would be best represented by a combination of eqn 18 (Holter and Urban 1992) for fecal water and eqn 21 (Weiss 2004) for urine. In addition to providing favourable comparisons to estimates in both the thermoneutral and cool periods, the noted equations promoted responsiveness, i.e. calculations were not limited to a single variable such as the body weight-based eqn 20 and eqn 24. Additionally, in considering lactating cows, when the study site total water intake was partitioned based on measured milk production and eqn 18 and eqn 21 results, respiratory cutaneous water accounted for 30.5% and 9.0% of outputs in the thermoneutral and cool period respectively. The thermoneutral value falls within the range specified by Appuhamy et al. (2015). With regard to the cool period percentage, in the absence of data relative to respiratory cutaneous water in conditions below the thermoneutral threshold, it is difficult to ascertain the accuracy of this figure; however, with temperatures at the study site averaging -12-3ºC, cool period respiratory cutaneous water is expected to be significantly lower than thermoneutral respiratory cutaneous water due to limited cutaneous water loss. Eqn 18 and 21 also produced an acceptable proportioning of fecal water to urine in both of the study periods. In healthy cattle, fecal matter accounts for the larger part of manure. The average composition is two-thirds feces and one-third urine; but, great variance has been noted (Weiss and St-Pierre 2010). For example, measured results from Appuhamy et al. (2015) produced mean results of 28.1 kg d^{-1} for fecal water and 23.5 kg d^{-1} for urine. Based on eqn 18 and eqn 21, fecal water and urine for lactating cows were proportioned as 34.9 to 27.0 kg d^{-1} and 42.5 to 28.5 kg $d^{-1}$for the thermoneutral and cool period respectively. The thermoneutral results for dry cows from eqn 18 and eqn 21 produced a low fecal water to urine differential of 3.1 kg d^{-1}; but, respiratory cutaneous water partitioning results (30.4 kg d^{-1}; 38.3%) were considered preferable to results from other equations. A comparison of output partitioning values for dry cows was not possible for cool period results as a measured total water intake value was not available. The ratio of fecal water to urine outputs from eqn 18 and eqn 21, however, was close to the average 2:1 ratio.

The total manure result from eqn 25 was deemed the best fit for all heifer weight groups. When applied to bred heifers (454 kg), eqn 25 resulted in a thermoneutral respiratory cutaneous water balance of 15 kg d^{-1} (29.1%) compared to 4.1 kg d^{-1} (8.0%) for eqn 18 and eqn 21. Additionally, eqn 18 and eqn 21 provided improbable urine to fecal water proportioning in the thermoneutral period with urine output exceeding fecal water production by 1.3 kg d^{-1}. In considering the younger heifer group (2-17 months), eqn 25 results were slightly lower than those from the other equations, provided a more feasible urine to fecal water ratio, and accommodated thermoneutral respiratory cutaneous water partitioning of 13 to 29% compared to 0 to 8%. Additionally, the equation was deemed the most responsive with inclusion of both DMI and body weight in calculations; body weight is an important element in determining feed quantities and water intake, and is of high relevance during the young heifer growth stage (Waldner and Looper 2002; ASAE 2005).

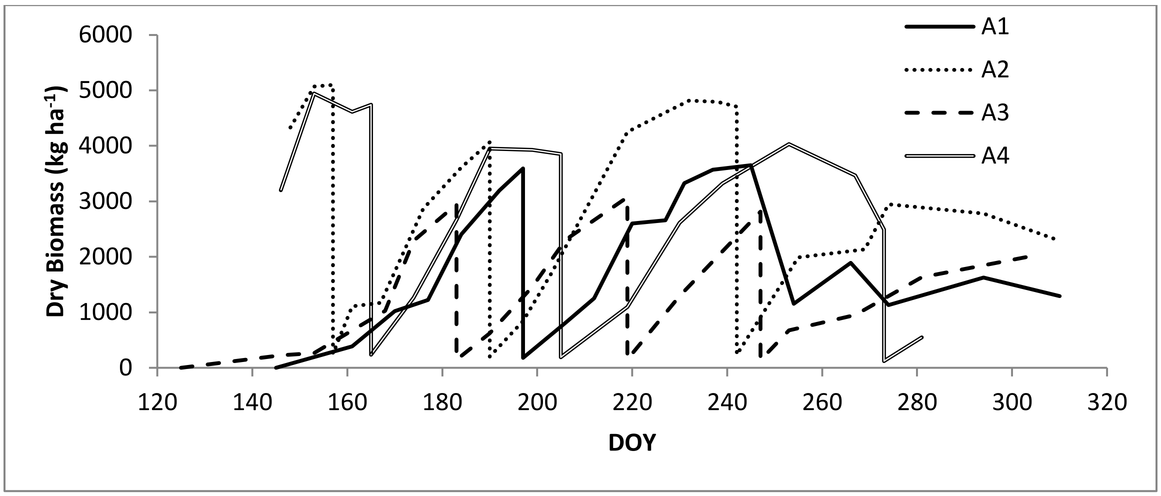
Overall, in applying eqn 18 and eqn 21 to lactating and dry cows, and eqn 25 to the heifer groups, the total manure output for the farm was 186.8 kg d^{-1} and 167.8 kg d^{-1} for the thermoneutral and cool period respectively. The higher value reflected the increased total water intake of the thermoneutral period.

Of note, while it is possible that estimates for FWI, DMI and cattle outputs may be improved with higher quality equations reflecting the impact of temperature on FWI and DMI, calculator development with this capability is beyond the scope of this study. Based on the research and analysis associated with this study, however, there is a high degree of confidence in the selected equations.

Appendix K Graphical and Tabular Summary of In-Situ Data Relating to Biomass and Soil Characteristics Collected from Study Sites A1 to A4 in Support of AAFC's Future Calibration of the DNDC Regionalized Alfalfa Algorithm and Biomass Partitioning

Biomass

(a) Results of Near Weekly Biomass Sampling at Sites A-1 to A-4 (Data regarding Site A1 previously discussed)



(b) Summary of Near Weekly Biomass Sampling Results at Sites A-1 to A-4 (Data regarding Site A1 previously discussed)

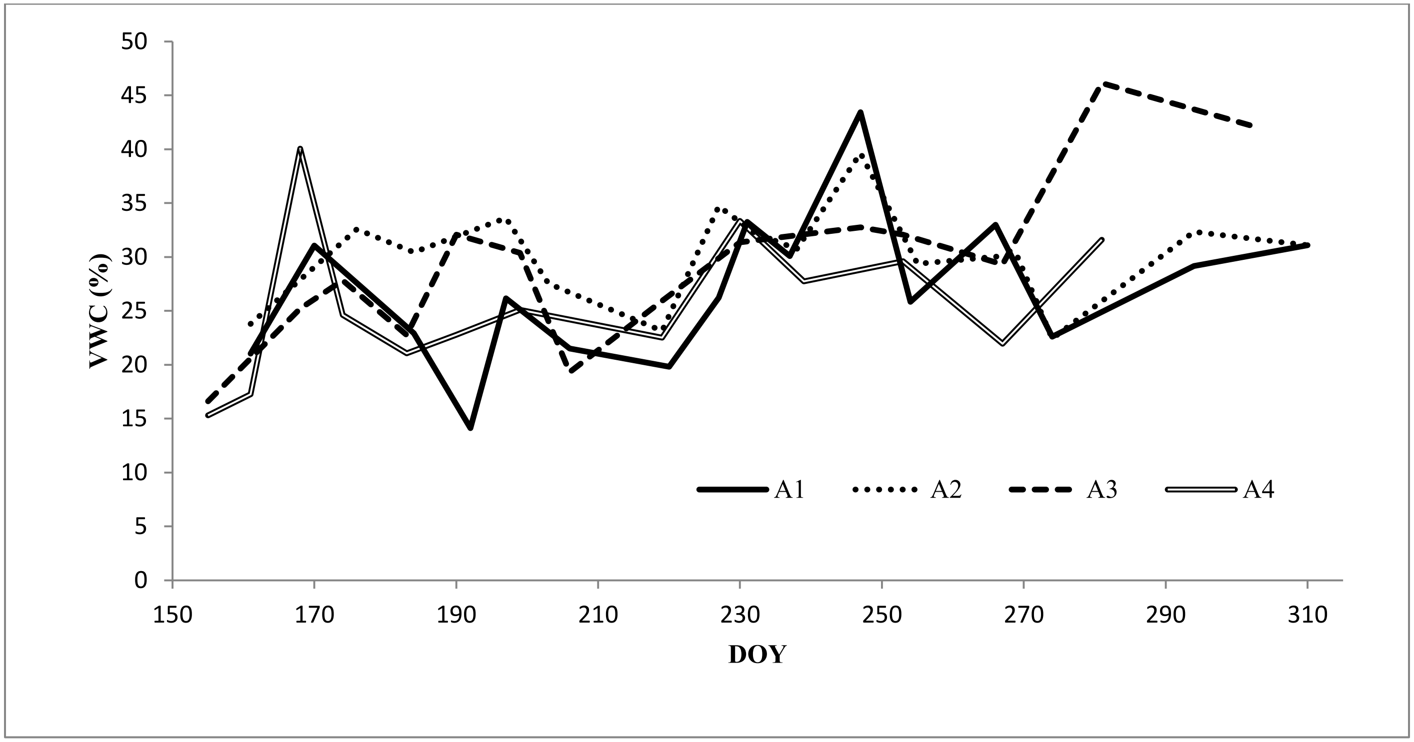
	Biomass (kg C ha^{-1})			
Study Site	1st Cut	2nd Cut	3rd Cut	Whole Season
A1	1,438.4	1,459.2		3,654.4
A2	2,040.0	1,627.2	1,882.0	5,843.7
A3	1,178.0	1,230.4	1,126.0	3,734.0
A4	1,896.4	1,540	1,612.0	5,103.4

Soil Characteristics

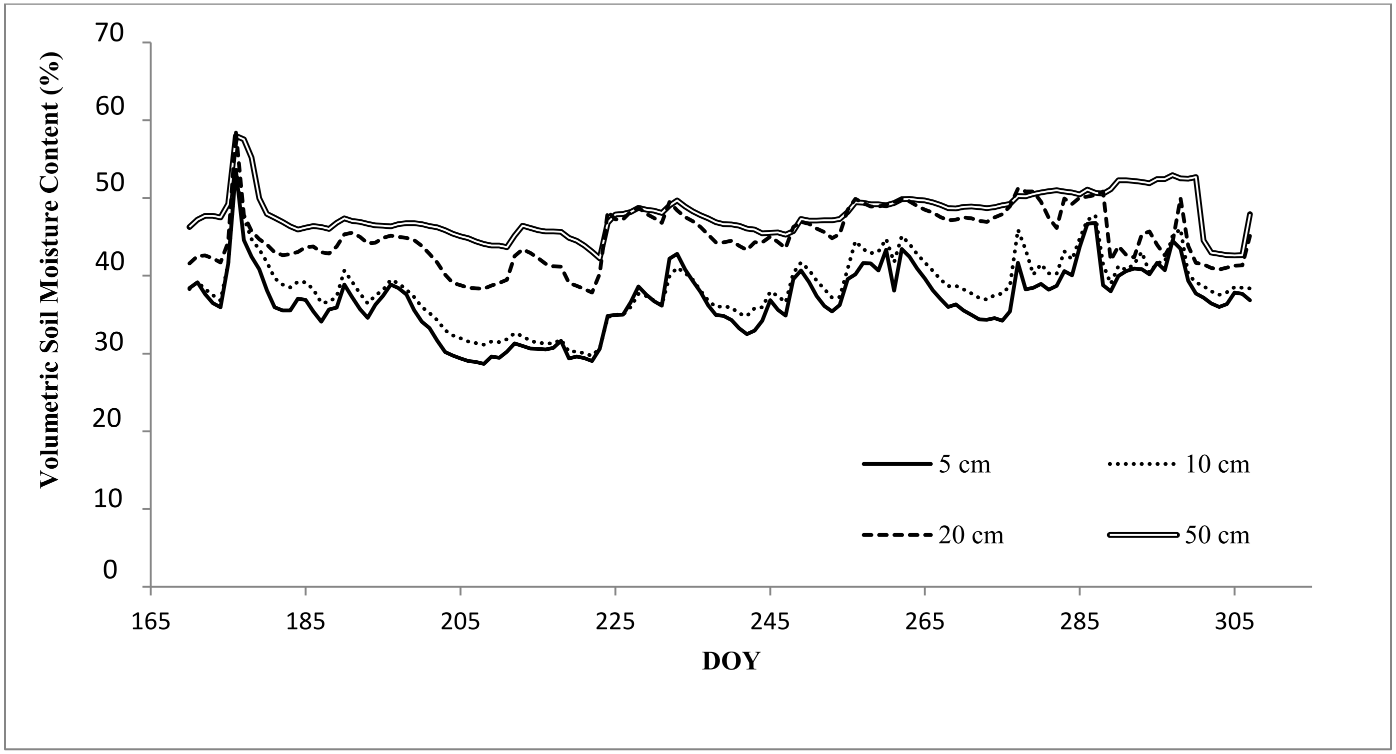
(c) Summary of Soil Characteristics from In-Situ Measurements and the USDA/Washington State University Hydraulic Properties Calculator for Sites A1 to A4. (Data regarding Site A1 previously discussed)

Study Site	Soil Texture	Clay Fraction (%)	pH	Bulk Density (g/cm^3)	Field Capacity (wfps)	Wilting Point (wfps)	Hydro-conductivity (cm/min)	Porosity (%)	Nitrate (µg/g)	Ammonia (µg/g)
A1	sandy loam	14	6.8	1.26	22.1	10.4	0.05	52	32.5	0.78
A2	sandy loam	15.1	6.8	1.42	22.6	10.9	0.05	46	13.5	0.65
A3	sandy loam	17	6.06	1.32	23.7	12.1	0.04	50	18	0.94
A4	sandy loam	14.7	7.44	1.4	21.9	10.9	0.05	47	14.6	1.15

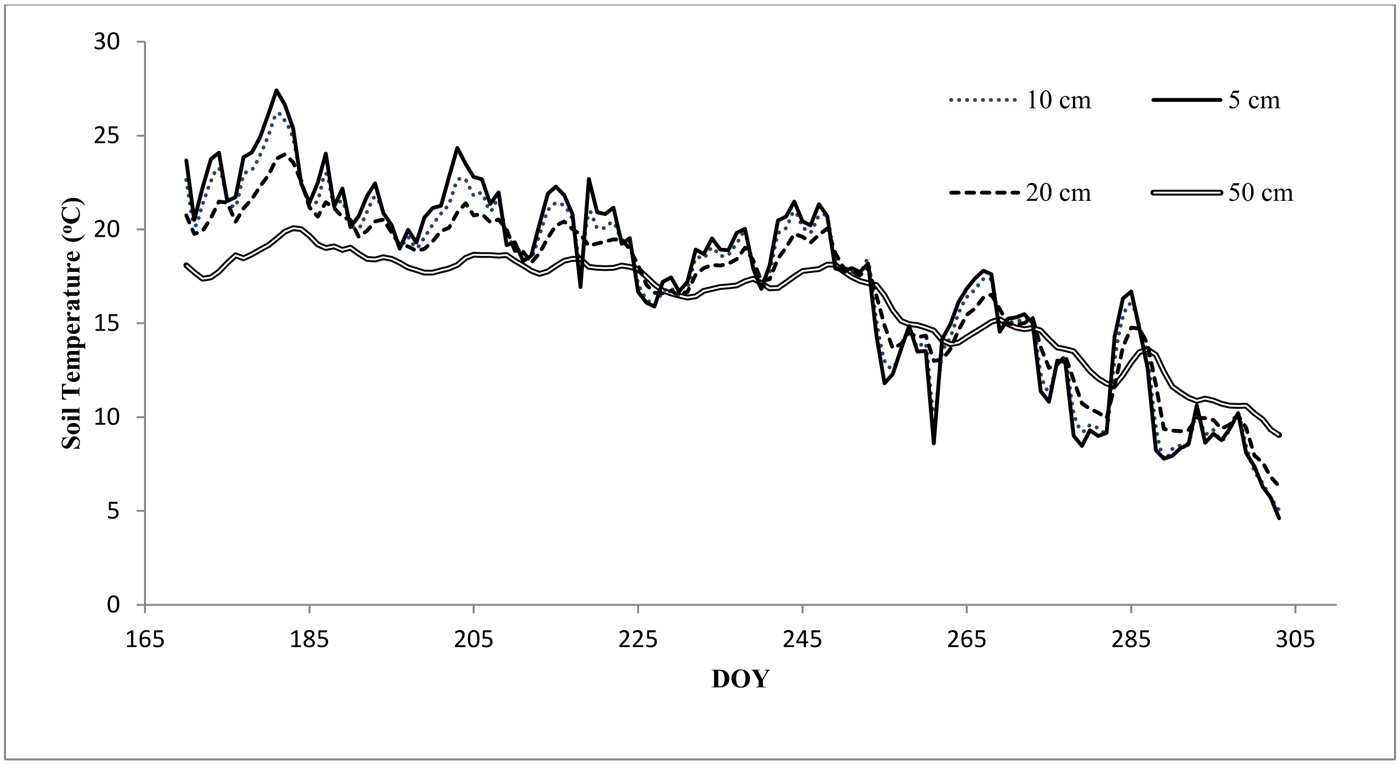
(d) Summary of Volumetric Soil Moisture Based on In-Situ Measurements for Sites A1 to A4. (Data regarding Site A1 previously discussed)



(e) Results of Volumetric Soil Moisture Recorded at 5, 10, 20 and 50 cm at Site A1 through the CS616 Water Content Reflectometers (Campbell Scientific, Logan UT).

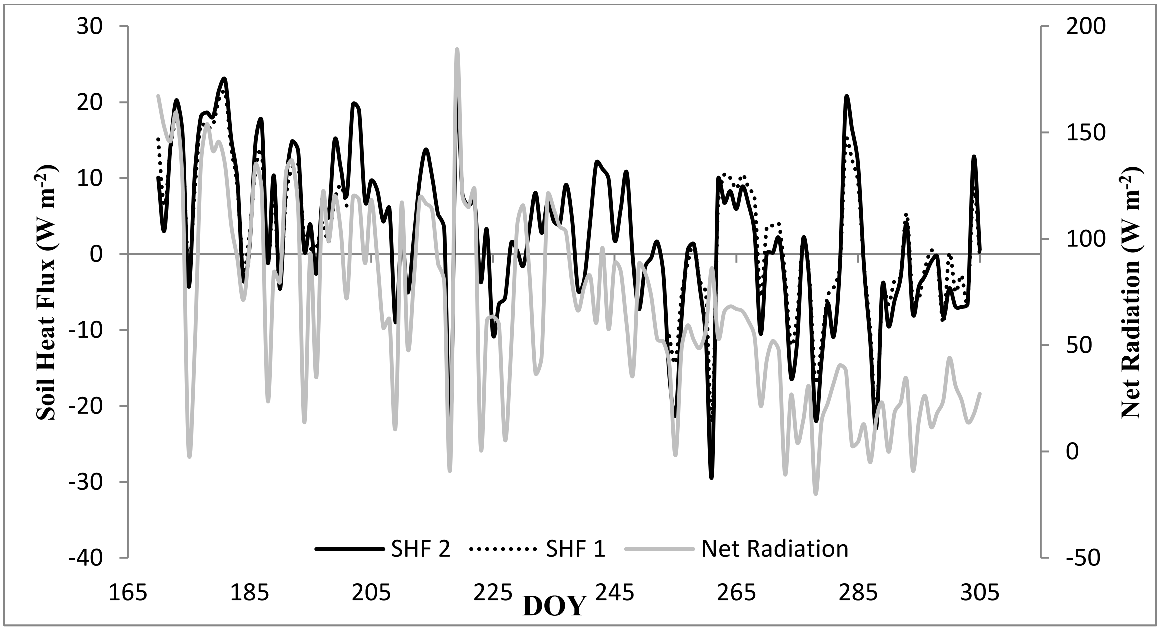


(f) Results of average soil temperatures recorded at 5, 10, 20 and 50 cm Site A-1 by TCAV-T Temperature Probe (Campbell Scientific, Logan UT).



Data summaries were also provided relating to soil temperature at 5 cm from the TCAV-E Averaging Thermocouples (Campbell Scientific, Logan UT) installed at Site A1

(g) Results for Heat Flux as measured by HFT3 Soil Heat Flux Plates (Campbell Scientific, Logan Utah) and Net Radiation as Measured by the NR-LITE Net Radiometer (Campbell Scientific, Logan, UT) at Site A1.



Appendix L Analysis of Water-use Efficiency Results for Field Crops and Pasture at the Morewood, Ontario, Study Site (A3) Based on Yield and Crop Water-use (ET) Values Used in WatBal-Dairy

Water-use efficiency (WUE) ranged from a low of 5.5 kg DM ha^{-1} mm^{-1} for pasture to 37.5 kg DM ha^{-1} mm^{-1} for corn silage (Table L(1)). WUE is known to vary widely, even within the same species, due to differences in field management practices, plant genetics and environmental factors such as radiation, temperature and precipitation (Zwart and Bastiannssen 2004; Sadras et al. 2012).

Table L(1) Water-use efficiency (WUE) of field crops and pasture in the field environment at the Morewood, Ontario, study site (A3) calculated as the ratio of dry matter yield (kg DM ha^{-1}) to the amount of evaporation (mm).

Crop	Field Area (ha)	Seasonal DM Yield by hectare (kg DM ha^{-1})	ET Estimation (mm)	Water-Use Efficiency (kg DM ha^{-1} mm^{-1})
Corn Silage	3.2	14,287	380.8	37.5
{rpaHMC*	10.2	7,494	397.6	18.8
Soybean	12.1	2,787	359.1	7.8
Alfalfa	32.8	7,620	410.9	18.5
Wheat	14.1	5,042	306.6	16.4
Total Crops	72.4	37,230	1,855	20.1
Total Pasture	21.0	1,988	362.6	5.5
Total Field Environment	93.4	39,218	2,217.6	17.7

* High Moisture Corn

The nature of the metabolic pathway of photosynthesis is one of the most important factors influencing WUE with C4 plants generally surpassing C3 plants in efficiency (Sadras et al. 2012). Corn, the only C4 crop grown at the study site, had the highest water productivity values with the WUE of silage (37.5 kg DM ha^{-1} mm^{-1}) almost double that of high moisture corn (grain) (18.8 kg DM ha^{-1} mm^{-1}). The high ratio of vegetative matter relative to grain and the high harvest index of silage contributed to the difference. The silage WUE value in this study fell to the high end of the range (27.7 to 38.1 kg DM ha^{-1} mm^{-1}) noted by Wagger and Cassel (1993) during a North Carolina study and fell near the mid-point of the range (30 to 46.8 kg DM ha^{-1} mm^{-1}) noted by Schroeder et al. (1980) in a North Dakota study. The value was also comparable to Australian multi-year study results of 39.1 to 45.3 kg DM ha^{-1} mm^{-1} and 28.6 to 40.6 kg DM ha^{-1} mm^{-1} which were calculated based on precipitation and irrigation totals (Neal et al. 2011). The high moisture corn WUE result also fell towards the higher end of the global range of 6 to 23 kg DM ha^{-1} mm^{-1} (Sadras et al. 2012), but was approximately mid-point of the range (11 to 27 kg DM ha^{-1} mm^{-1}) identified by Zwart and Bastiannssen (2004) based on a review of 27 corn studies stemming primarily from China and the United States. The higher WUE noted for alfalfa (18.5 kg DM ha^{-1} mm^{-1}) was consistent with results for perennials, and reflects multiple cuts and the high percentage of plant biomass harvested (Putman 2012). The study result was higher than the cumulative seasonal WUE (11.71 and 13.03 kg DM ha^{-1} mm^{-1}) noted by Attram (2014) for irrigated alfalfa in Alberta; but, was lower than the irrigated results of 29 kg DM ha^{-1} mm^{-1} in a New Zealand study (Brown et al. 2005) and 28.3 kg DM ha^{-1} mm^{-1} in a Chinese study (Tingwu et al. 2005). In contrast to corn and alfalfa, soybean had a low efficiency of 7.8 kg DM ha^{-1} mm^{-1}. The value fell just below the mid-point of the global range of 6 to 10 kg DM ha^{-1} mm^{-1} (Sadras et al. 2012), and may be low relative to average Canadian soybean productivity values which generally trend towards the higher end of the scale (Wani and Heng 2012). It is difficult to assess the accuracy of the spring wheat WUE value of 18.5 kg DM ha^{-1} mm^{-1} as most studies report WUE based on wheat grain yield as opposed to straw yield, or provide WUE values for winter wheat. Additionally, unlike winter wheat which has an almost linear relationship between grain and wheat production (1 to 1.67 relationship), the relationship between spring wheat grain and straw yields is highly variable (Engel et al. 2005); this impedes comparison to existing grain WUE results. Nevertheless, there is strong confidence in the WUE value based on the farmer's input for dry matter yield and the ET estimate which fell within the 200 to 500 mm global range (Sadras et al. 2012). Assessment of the pasture WUE of 5.5 kg DM ha^{-1} mm^{-1} was hampered by the absence of existing studies with similar growing conditions and pasture composition, (i.e. red clover, alfalfa, timothy and orchard grass); WUE is known to be influenced by plant species, as well as environmental conditions and management decisions (Moot 2012). For example, in New Zealand, the mean 25 year WUE average for rain-fed ryegrass/white clover pasture was 12.3 kg DM ha^{-1} mm^{-1} (Martin et al. 2006), rain-fed fertilized cocksfoot had an annual WUE of 38 kg DM ha^{-1} mm^{-1} and unfertilized cocksfoot an annual WUE of 17 kg DM ha^{-1} mm^{-1}. Overall, however, there was confidence in the WUE values based on the OMAFRA yield estimations and the method of ET estimation.

Appendix M Analysis of FWI equation results in WatBal-Dairy for all cattle life stages

FWI equation estimates generally compared well to measurements during the thermoneutral period at the Morewood farm (A3) (Table 22). Eqn 10 provided reasonable FWI with only a small over-estimations of 6.7% for 33 lactating cows and 10.8% for 10 dry cows. At the farm level, the total over-estimation of 320 kg d^{-1} for both groups represents less than the actual daily water intake of three lactating cows. Eqn 7 was used to estimate FWI for all heifer groups; the regression model results relied on the percentage of dry matter in the diet, DMI and the percentage of crude protein in the dry matter. Results for bred heifers (17-24 months) were highly favourable with a total under-estimation of 11% for 13 animals, while results for young heifers (2-17 months) showed notable variation with an under-estimation 95 kg d^{-1} or 26.5% for 16 animals. However, the combined FWI of all heifer groups (129 kg d^{-1}) was only 3.8% less than actual intake; roughly equivalent to the measured daily total water intake of a single lactating cow (124.8 kg d^{-1}).

Overall, the variation in the estimates and measured data, particularly for young heifers, brings to light the sensitivity of the FWI equations to dynamic changes in the cattle environment and the need for accurate feed inputs. The diet and FWI for young heifers were calculated based on farmer inputs and measurements respectively; however, there was no allowance for changes in feed and water consumption associated with heifer growth, i.e. heifers identified as 2-6 months with an average body weight of 136 kg and heifers 6-17 months with an average body weight of 272 kg were allotted the same diet. With a more accurate accounting of diet inputs, it is likely that the overall estimate result would improve. For example, by increasing DMI in eqn 7 by 1 kg d^{-1} for the 11 heifers identified by the farmer in the 272 kg weight group, the estimated FWI by animal would be 22.3 kg d^{-1}; only 0.1 kg d^{-1} below the measured value.