A quantitative assessment of Beneficial Management Practices to reduce carbon and reactive nitrogen footprints and phosphorus losses on dairy farms in the US Great Lakes region

Karin Veltman, C. Alan Rotz, Larry Chase, Joyce Cooper, Pete Ingraham, R. César Izaurralde, Curtis D. Jones, Richard Gaillard, Rebecca A. Larson, Matt Ruark, William Salas, Greg Thom, Olivier Jolliet

Agricultural Systems 166 (2018) 10–25

Keywords:
- Dairy farm
- Carbon footprint
- Reactive nitrogen footprint
- Beneficial Management Practices (BMP)
- Whole-farm model simulation
- Milk production
- Economic assessment

ABSTRACT

Assessing and improving the sustainability of dairy production is essential to secure future food production. Implementation of Beneficial Management Practices (BMP) can mitigate GHG emissions and nutrient losses and reduce the environmental impact of dairy production, but comprehensive, whole-farm studies that evaluate the efficacy of multiple BMPs to reduce multiple environmental impacts and that include an assessment of productivity and farm profitability, are scarce. We used a process-based model (IFSM) to assess the efficacy of (10+) individual BMPs to reduce the carbon (C) footprint expressed per unit of milk produced of two model dairy farms, a 1500 cow farm and a 150 cow farm, with farming practices representative for the Great Lakes region. In addition to the C footprint, we assessed the effect of BMP implementation on the reactive nitrogen (N) footprint and total phosphorus (P) losses (per unit of milk produced), as well as milk production and farm profitability. We evaluated individual farm-component specific BMPs, that is, 5 dietary manipulations, 3 (150 cow farm) or 4 (1500 cow farm) manure interventions, and 6 field interventions, as well as an integrated whole-farm mitigation strategy based on the best performing individual BMPs. Our results show that reductions in the C footprint expressed per unit of milk are greatest with individual manure management interventions (4–20% reduction) followed by dietary manipulations (0–12% reduction) for both farm types. Field management BMPs had a modest effect on reducing this footprint (0–3% reduction), but showed substantial potential to reduce the reactive N footprint (0–19% reduction) and P losses (1–47% reduction). We found that the whole-farm mitigation strategy can substantially reduce the C footprint, reactive N footprint and total P loss of both farms with predicted reductions of approximately 41%, 41% and 46% respectively, while increasing milk production and the net return per cow by approximately 11% and 27%. To contextualize IFSM predictions for the whole-farm mitigation, we compared components of IFSM predictions to those of three other process-based models (CNCPS, Manure-DNDC and EPIC). While we did observe differences in model predictions for individual flows (particularly P erosion and P leaching losses), with exception of the total P loss, the models generally predicted similar overall mitigation potentials. Overall, our analysis shows that an integrated set of BMPs can be implemented to reduce GHG emissions and nutrient losses of dairy farms in the Great Lakes region without sacrificing productivity or profit to the farmer.

https://doi.org/10.1016/j.agsy.2018.07.005

Received 28 August 2017; Received in revised form 1 May 2018; Accepted 5 July 2018

© 2018 Elsevier Ltd. All rights reserved.

Corresponding author.
E-mail address: veltmank@umich.edu (K. Veltman).
1. Introduction

Assessing and improving the sustainability (WCED, 1987) of dairy production is essential to meet the nutritional needs of a growing population and to secure future food production. Dairy products represent an important and affordable source of many essential dietary nutrients, including calcium, vitamin D and potassium, which are nutrients of public health concern in the US (Cifelli et al., 2016; Capper and Bauman, 2013; Drewnowski, 2011). Because of their nutritional value, dairy products are included in dietary guidelines world-wide (Capper and Bauman, 2013). Dairy production is, however, a contributor to environmental challenges at local, regional and global scales (Steiner et al., 2006; Pelletier and Tyedmers, 2010; Bouwman et al., 2013).

Dairy production is a source of greenhouse gas emissions (GHG), primarily methane (CH4) and nitrous oxide (N2O), and thus contributes to global warming. Dairy production is reportedly responsible for 2.7% of global GHG emissions (Gerber et al., 2010). In the US, the dairy sector is responsible for approximately 1.9% of total US GHG emissions, with enteric CH4 as the single most important source of GHG emissions, followed by CH4 from manure management (Thoma et al., 2013). In addition, crop-livestock production systems are the largest cause of human alteration of global nitrogen (N) and phosphorus (P) cycles (Howarth et al., 2002; Boyer et al., 2004; Villalba et al., 2008; Bouwman et al., 2013). Excessive fertilizer application and a relatively low nutrient use efficiency by crops and animals results in large losses of reactive N (any form of N other than N2) and P to the environment, with repercussions for human health (e.g. secondary particle formation due to ammonia (NH3) emission and drinking water contamination by nitrate (NO3−)) and environmental quality (e.g. eutrophication of lakes and coastal waters and exacerbation of hypoxic zones) (Schindler et al., 2008; Davidson et al., 2011). At a whole-farm scale, generally 15 to 55% of the total N input to the farm (including N fixation and N deposition) and 56 to 74% of the total P input to the farm is converted into edible and non-edible products (e.g. grain, forage, animals and milk) (Gerber et al., 2014; Powell et al., 2017). Most of the remaining nutrients are lost to the environment. Ammonia volatilization due to manure management and soil application of manure is often the largest loss pathway for N, followed by N leaching from soils to the hydrosphere (US EPA, 2014; Powell et al., 2014; Powell and Rotz, 2015). Phosphorus is not volatile and it is primarily lost through erosion and run-off from soils.

Implementation of Beneficial Management Practices (BMPs) can mitigate GHG emissions and nutrient losses and reduce the environmental impact of dairy production. Several BMPs have been developed, predominantly focusing on the mitigation of GHG emissions from individual farm components such as the animal, the manure storage and the field (e.g. Hristov et al., 2013; Montes et al., 2013; Knapp et al., 2014). In dairy production systems, N, P and carbon (C) flows are, however, interrelated; thus, effective mitigation of one pollutant can increase emissions of another pollutant. For example, Dijkstra et al. (2011) suggested that dietary strategies that reduce N excretion from dairy cows may increase enteric CH4 emissions. Similarly effective mitigation of N losses in one form (e.g. NH3) is often offset by N losses in other forms (e.g. N2O or NO3−) (Gerber et al., 2013). Field studies have shown that subsurface injection of manure can substantially reduce N losses from NH3 volatilization relative to broadcast application (~40–98% reduction) (Dell et al., 2011; Duncan et al., 2017), but a portion of that N conservation is offset by increased emissions of the GHG N2O (~84%–152%) (Duncan et al., 2017). In addition to interactions between N, P and C flows, nutrient flows between farm components, including the animal herd, the manure management system, the field, and the feed, are strongly linked. Altering one component of this nutrient cycle can have major effects on nutrient flows to or from other farm components. To prevent ‘pollutant swapping’, BMPs should not be evaluated in isolation but rather in a whole-farm context, so that the multiple interacting effects are adequately considered. In addition, on-farm economic cost is an important and often decisive factor in the adoption of any new farming practice. Beneficial Management Practices that jeopardize production (milk, crop yield), and/or are associated with high initial implementation costs and a decrease in long-term profitability are unlikely to be adopted by farmers and as such cannot generally be considered sustainable.

A holistic approach is thus needed that evaluates the efficacy of BMPs to mitigate multiple environmental impacts in a whole-farm context, and that includes an assessment of productivity and profitability (Rotz et al., 2005; Gerber et al., 2013). It is practically and economically infeasible to empirically test all combinations of BMPs at a whole farm scale. Whole-farm process based models are well-suited tools to efficiently test different combinations of BMPs (Rotz et al., 2005; Beukes et al., 2011; Del Prado et al., 2013). These models can account for the underlying physical and chemical processes influencing N, P, and C flows, predict the effect of BMP implementation on milk production and crop yield, and some models (e.g. the Integrated Farm System Model (IFSM)) can account for economic aspects. Process-based models have been employed to test the implementation of BMPs on whole-farm environmental impacts (e.g. Weiske et al., 2006; Dutreuil et al., 2014; Duncan et al., 2017). Most studies, however, have focused on testing the potential of a small set of BMPs to reduce one particular environmental impact, often for a single farm test case. Currently, comprehensive, whole-farm studies that evaluate the efficacy of multiple BMPs to reduce multiple environmental impacts for distinct farm types in different locations, and that include an assessment of productivity and farm profitability, are limited.

Here, we assess the potential of multiple BMPs to reduce the C footprint, reactive N footprint and P loss of two representative dairy farms in the US Great Lakes region, without compromising milk production and farm profitability. Our farms are located in Wisconsin and New York, which are two of the major dairy producing states in the US, together accounting for 21% of the total US milk production in 2016 (USDA ERS). Identifying and quantifying opportunities to reduce farm GHG emissions in these states can help the US Dairy Industry to achieve its (voluntary) commitment to reduce total GHG emissions of the dairy food supply chain by 25% (from 2007 levels) by 2020 (Innovation Center for US Dairy, 2016). Also, Wisconsin and New York are partly located in the US Great Lakes region, where nutrient pollution of surface waters due to agricultural run-off is a long-standing and recurring problem (Robertson and Saad, 2011; Michalak et al., 2013). Yet, agriculture is an important contributor to the economy of both states and retaining these agricultural industries is essential.

The objectives of this study were to: i) evaluate the efficacy of individual BMPs on reducing the C footprint of two representative dairy farms in the Great Lakes region and to simultaneously assess the effect on the reactive N footprint, P loss, milk production and farm profitability and to ii) identify and assess an integrated set of BMPs that can be applied to reduce the C footprint, reactive N footprint and P loss of the production system without sacrificing productivity or profit. The environmental footprints are defined as the effect on the environment expressed per unit of product produced and include an assessment of impacts associated with pre-farm sources (such as the production of purchased feed) (Rotz et al., 2016a). Phosphorus loss represents the total loss of P from the farm to the environment; excluding P losses associated with pre-farm sources.
2. Methods

2.1. Conceptual approach

First, we defined two baseline farms that are representative of current dairy farming practices in the US Great Lakes region and that form the reference point for the BMP evaluation. As farm size in the Great Lakes region is variable and known to influence dairy farming practices as well as environmental impacts (e.g. Powell and Rotz, 2015), we developed two baseline farms with different herd sizes: a 1500 cow (lactating + non lactating cows) farm and a 150-cow farm.

Second, we identified farm-specific BMPs for the three specific farm components, feed, manure handling, and the field, which have been shown to reduce direct and/or indirect (NH3 and NO3−) GHG emissions. The BMPs were characterized using the Integrated Farm System Model (IFSM4.3) (Rotz et al., 2016a). The characterization of BMPs (in a simulation system) is not trivial due to the multiple interactions that can occur in a whole-farm context, particularly between the feed and the field, which can hamper the comparison among the baseline and individual BMPs. We used the following set of rules (per farm type), to ensure a consistent comparison among the baseline and individual BMPs: 1. Herd size was fixed; 2. Milk production was allowed to vary, however, only if the strategy increased production (otherwise feed BMPs were adjusted to maintain milk production); 3. Cultivated area varied slightly to maintain a long term average of no purchase or selling of forage or grain crops produced on farm; 4. Supplementary feeds were purchased to meet energy and protein requirements of the herd; 5. The fraction of exported manure was fixed. This rule applied to the 1500-cow farm only, as all manure was applied to cropland on the 150-cow farm.

Third, we used IFSM4.3 to simulate the baseline scenarios and the individual BMPs, changing one management practice at a time. For each scenario, representative farms were simulated over 25 years of weather to obtain GHG emissions and nutrient losses per farm component. We also evaluated BMP performance in terms of milk production (kg/cow/year, corrected to 4% fat and 3.3% protein), the net return to manure and the GHG emissions and N losses associated with secondary sources, i.e. emissions occurring during the manufacture or production of fuel, electricity, machinery, fertilizer, pesticide and plastic used in the production of feeds and maintenance of animals (hereafter: resource production). We calculated three environmental metrics: C footprint, reactive N footprint, and P loss across farm boundaries, all allocated per kg of milk produced, to facilitate comparison of the individual BMP scenarios to the baseline and each other. We also evaluated BMP performance in terms of milk production (kg/cow) and long-term average annual profitability (net return to management, $/cow).

Finally, we identified and integrated the best performing individual BMPs into one whole-farm, mitigation strategy per farm. The whole-farm mitigation strategies were simulated in IFSM and evaluated in terms of their efficacy to reduce whole-farm C and reactive N footprints, and P losses, without compromising economic sustainability. Three other process-based models, an animal model (CNCPS), a field model (EPIC) and a biogeochemical farm model (Manure-DNDC) were employed to contextualize IFSM predictions of milk production, GHG emissions and nutrient losses at the animal, field and farm scales. The IFSM was used as a baseline model, as it is presently the most comprehensive whole-farm model available, i.e. it estimates economic aspects along with GHG emissions and nutrient losses associated with resource production, as well as GHG emissions and nutrient losses directly resulting from milk production. IFSM was also shown to perform well in a cross-comparison study of various process-based models (Veltman et al., 2017).

2.2. Baseline dairy farms

The two baseline dairy farms (Table 1) were developed based on the project team's expertise. For the 1500-cow farm, the baseline scenario was partly based on a previously-studied commercial dairy farm in NY state (Veltman et al., 2017). Since this commercial dairy farm already employs some BMPs (e.g. anaerobic digestion in manure management), the farm was adapted to derive the baseline scenario. External experts (Dane County Conservationists, Madison, WI) were consulted to set up the baseline scenario for a typical 150-cow farm in Wisconsin. The 1500-cow farm was placed in Skaneateles, NY, at the location of the previously simulated commercial dairy farm (Veltman et al., 2017). The 150-cow farm was placed near Arlington, WI, near the Arlington Agricultural Research Station (https://arlington.ars.wisc.edu/). This location was chosen because climate and soil data were readily available.

2.2.1. 1500-cow farm in New York State

The 1500-cow farm consisted of 1500 milk cows (Holstein) and 1180 replacement heifers (583 older heifers and 597 young heifers; 38% replacement rate). Milk production averaged 9527 kg/cow/year corrected to 4% fat and 3.3% protein. The animals were fed a total mixed ration (TMR) consisting of alfalfa silage, corn silage, dry corn grain, soybean meal and expeller soybean meal with the diet crude

Table 1
Description of the baseline farms.

<table>
<thead>
<tr>
<th>Farm component</th>
<th>Content/description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm Total cropland (1500-cow farm)</td>
<td>1284 ha</td>
</tr>
<tr>
<td>Farm Total cropland (150-cow farm)</td>
<td>130 ha</td>
</tr>
<tr>
<td>Animal Cows (1500-cow farm)</td>
<td>1500 lactating + dry cows, 1180 replacement heifers</td>
</tr>
<tr>
<td>Animal Cows (150-cow farm)</td>
<td>150 lactating + dry cows, 130 replacement heifers</td>
</tr>
<tr>
<td>Animal Milk production (1500-cow farm)</td>
<td>9527 kg/cow/year (corrected to 4% fat and 3.3% protein)</td>
</tr>
<tr>
<td>Animal Milk production (150-cow farm)</td>
<td>10,134 kg/cow/year (corrected to 4% fat and 3.3% protein)</td>
</tr>
<tr>
<td>Feed Corn silage: alfalfa silage ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Feed Forage level (lactating cows) % of total DM intake</td>
<td>65%</td>
</tr>
<tr>
<td>Feed NDF digestibility</td>
<td>Low</td>
</tr>
<tr>
<td>Feed Feed efficiency (kg milk / kg feed DM)</td>
<td>1.5</td>
</tr>
<tr>
<td>Feed Fat intake (kg fat / cow / day)</td>
<td>0.4</td>
</tr>
<tr>
<td>Feed Diet crude protein (CP)</td>
<td>17%</td>
</tr>
<tr>
<td>Barn Type (1500-cow farm)</td>
<td>Free-stall (heifers, lactating + dry cows)</td>
</tr>
<tr>
<td>Barn Type (150-cow farm)</td>
<td>Bedded pack (heifers), free-stall (lactating + dry cows)</td>
</tr>
<tr>
<td>Bedding (1500-cow farm)</td>
<td>Straw</td>
</tr>
<tr>
<td>Bedding (150-cow farm)</td>
<td>Sand (lactating + dry)</td>
</tr>
<tr>
<td>Bedding (150-cow farm) (heifers)</td>
<td>Straw / corn stalk</td>
</tr>
<tr>
<td>Manure management &amp; storage Management (1500-cow farm)</td>
<td>Manure handled as a slurry (8–10% DM) (no separation)</td>
</tr>
<tr>
<td>Manure management &amp; storage Storage (1500-cow farm)</td>
<td>6 month lined earthen storage</td>
</tr>
<tr>
<td>Manure management &amp; storage Management (150-cow farm)</td>
<td>Manure handled as a slurry (8–10% DM) (no separation); Heifer manure handled as solid</td>
</tr>
<tr>
<td>Manure management &amp; storage Storage (150-cow farm)</td>
<td>6 month storage tank for slurry</td>
</tr>
<tr>
<td>Field management Crops (1500-cow farm)</td>
<td>Alfalfa, corn grain, corn silage, grass</td>
</tr>
<tr>
<td>Field management Crops (150-cow farm)</td>
<td>Alfalfa, corn grain, corn silage, oat silage seeded with alfalfa</td>
</tr>
<tr>
<td>Manure application Manure application</td>
<td>Broadcast application, no incorporation into soil</td>
</tr>
</tbody>
</table>
protein (CP) content set at 17%. All animals were fed to meet NRC (2001) requirements for energy and P. All animals were housed in mechanically ventilated free stall barns with straw bedding. All manure was removed daily from the barns. The manure was handled as slurry (8–10% DM) with 6 month manure storage. Approximately 88% of the manure was broadcast applied to cropland with no incorporation into the soil with the remaining 12% exported from the farm.

The farm cultivated about 1284 ha of cropland. The land was gently sloping and soil P was at a high level (50–100 ppm). The soil was a shallow loam with 22% clay, 54% silt, 24% sand and a water holding capacity of 182 mm. Three crops were grown: corn, alfalfa, and grass.

There was no pasture land on the farm. All forage and grain needed was produced on the farm with crop area set to provide sufficient feed on average over a 25 year simulation. Corn (relative maturity index of 99 days) was grown on 720 ha of the cropland. The corn land received 80% of the total manure plus 35 kg N/ha of fertilizer applied pre-planting and 12 kg N/ha of fertilizer applied post planting (SI Table 3). In addition, the corn land received 16.3 kg P2O5/ha, 58.7 kg K2O/ha, and an average of 0.75 t lime/ha/year. Alfalfa was grown on 414 ha in a 4-year stand including the establishment year. The alfalfa land received 5% of the total manure at seeding in addition to 54.1 kg K2O/ha and 1.3 t/ha/yr of lime. Grass was grown on 150 ha. The grass land received...

### Table 2
Individual BMPs for the 1500- and 150-cow farm.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Characteristics of BMP implementation</th>
<th>Expected effect*</th>
<th>Reference*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feed</strong></td>
<td>Forage fraction of diet for lactating cows reduced from 65% to 50% of DM by replacing silage (both alfalfa and corn silage) with corn grain and protein supplements</td>
<td>enteric CH4 ↓</td>
<td>(Knapp et al., 2014); (Hristov et al., 2013)</td>
</tr>
<tr>
<td>50% forage rations</td>
<td>NDF digestibility</td>
<td>milk †</td>
<td>(Knapp et al., 2014); (Hristov et al., 2013)</td>
</tr>
<tr>
<td>High NDF digestibility</td>
<td>Feed efficiency increased from –1.5 to 1.65 kg milk/kg feed DM.</td>
<td>milk †</td>
<td>(Hristov et al., 2013); (Vandelseaar et al., 2016)</td>
</tr>
<tr>
<td>High fat</td>
<td>Supplemental fat in diet of lactating cows increased from 0.5 to 1 kg/day per cow (i.e. from –2% to –5% fat on a DM basis).</td>
<td>milk †, enteric CH4 ↓</td>
<td>(Knapp et al., 2014); (Hristov et al., 2013)</td>
</tr>
<tr>
<td>Reduced protein</td>
<td>Diet protein of lactating cows reduced from 17% to 14% by decreasing the fraction of soybean meal in the diet.</td>
<td>urinary N ↓, NH3 ↓</td>
<td>(Montes et al., 2013); (Powell and Rotz, 2015)</td>
</tr>
<tr>
<td><strong>Manure management</strong></td>
<td>Bedded pack barn for the heifers replaced with free stall barns.</td>
<td>barn floor NH3, N2O ↓</td>
<td>(Rotz et al., 2016b)</td>
</tr>
<tr>
<td>Free stall for heifers (150 cows)</td>
<td>Unsealed covered manure storage is used.</td>
<td>storage N2O ↓</td>
<td>(Rotz, 2004); (Montes et al., 2013)</td>
</tr>
<tr>
<td>Covered storage (150 cows)</td>
<td>Sealed covered manure storage with flake to burn biogas produced</td>
<td>storage CH4 ↓</td>
<td>(Rotz, 2004); (Montes et al., 2013)</td>
</tr>
<tr>
<td>Sealed with flare</td>
<td>Separator used to remove portion of manure solids, which are used for bedding. Remaining separated solids exported from farm</td>
<td>storage CH4 ↓, NH3↓, (NH3 loss land application ↓)</td>
<td>(Holly et al., 2017)</td>
</tr>
<tr>
<td>Separation (1500 cows)</td>
<td>Anaerobic digester used to create biogas and electricity used on-farm. Digestate is handled as a slurry and stored in a bottom-loaded tank for 6 months prior to land application.</td>
<td>storage CH4 ↓, NH3↓, (NH3 loss land application ↑)</td>
<td>(Montes et al., 2013); (Holly et al., 2017)</td>
</tr>
<tr>
<td><strong>Digestion (1500 cows)</strong></td>
<td>Manure anaerobic digestion followed by separation is used.</td>
<td>storage CH4 ↓, N2O ↑</td>
<td>(Montes et al., 2013); (Holly et al., 2017)</td>
</tr>
<tr>
<td>Digestion and separation (1500 cows)</td>
<td>Annual grass cover crop following corn at a seeding cost of $50/ha.</td>
<td>erosion N &amp; P losses ↓, N leaching ↓</td>
<td>(Sharpley and Smith, 1991); (Strock et al., 2001); (Tonitto et al., 2006); (Krueger et al., 2012)</td>
</tr>
<tr>
<td><strong>Field management</strong></td>
<td>Winter rye crop established following corn silage harvest in the fall and harvested in the spring as silage for animal feed. Feeding N fertilizer application rate reduced from 60 kg N/ha to 45 kg N/ha (Table 5) to meet crops nutrient needs.</td>
<td>N leaching ↓</td>
<td>(Sharpley and Smith, 1991); (Strock et al., 2001); (Tonitto et al., 2006); (Krueger et al., 2012)</td>
</tr>
<tr>
<td>Cover crop</td>
<td>Winter rye crop established following corn silage harvest in the fall and harvested in the spring as silage for animal feed. Feeding N fertilizer application rate reduced from 60 kg N/ha to 45 kg N/ha (Table 5) to meet crops nutrient needs.</td>
<td>N leaching ↓</td>
<td>(Sharpley and Smith, 1991); (Strock et al., 2001); (Tonitto et al., 2006); (Krueger et al., 2012)</td>
</tr>
<tr>
<td>Rye double crop</td>
<td>1500-cow farm: no change made in the N fertilizer application rate as whole-farm benefit from reduced N loss was small (Table 5).</td>
<td>N leaching ↓</td>
<td>(Syswerda et al., 2012); (Shipitalo et al., 2013)</td>
</tr>
<tr>
<td>No till</td>
<td>20% of the collected manure diverted from corn land and applied to rye land. 150-cow farm: oats replaced by winter rye. Pre-planting N fertilizer application rate reduced from 45 kg N/ha to 35 kg N/ha (Table 5) to meet crops nutrient needs.</td>
<td>N leaching ↓</td>
<td>(Syswerda et al., 2012); (Shipitalo et al., 2013)</td>
</tr>
<tr>
<td>No-till establishment used for all crops with no incorporation of manure. 1500-cow farm: no change in fertilizer application needed (SI Table 5).</td>
<td>N leaching ↓</td>
<td>(Syswerda et al., 2012); (Shipitalo et al., 2013)</td>
<td></td>
</tr>
<tr>
<td><strong>Summer application</strong></td>
<td>Nine month manure storage emptied in the spring and again in early summer. 1500-cow farm: N fertilizer application rate on corn land reduced from 35 kg N/ha to 20 kg N/ha (Table 5).</td>
<td>N leaching ↓</td>
<td>(Robertson and Vitousek, 2009); (Rotz, 2004)</td>
</tr>
<tr>
<td>Incorporate same day</td>
<td>Manure incorporated into the soil the same day of application. 1500-cow farm: N fertilizer use reduced 12 kg N/ha. 150-cow farm: N fertilizer use reduced to 40 kg N/ha.</td>
<td>NH3 ↓, potentially N2O ↑</td>
<td>(Thompson and Mesinger, 2002); (Montes et al., 2013)</td>
</tr>
<tr>
<td>No-till with injection</td>
<td>Manure incorporated into the soil the same day of application. 1500-cow farm: N fertilizer use reduced 12 kg N/ha. 150-cow farm: N fertilizer use reduced to 40 kg N/ha.</td>
<td>N leaching ↓, NH3 volatilization ↓</td>
<td>(Dell et al., 2011); (Hou et al., 2015); (Duncan et al., 2017)</td>
</tr>
</tbody>
</table>

Note: BMPs are applicable to both farm types (150-cow farm and 1500-cow farm) unless mentioned otherwise. *Expected effect of BMP on GHG emissions of farm component as well as field nutrient losses with literature references in “Reference” column. In parentheses potential effects on GHG emissions from other farm components.

---

15% of the total manure, in addition to 60 kg N/ha, 2.1 kg P₂O₅/ha, and 0.75 ton of lime/ha/year. Field management practices were characterized as conventional till (chisel plow, field cultivator, planting) (SI Table 4). Alfalfa silage was harvested in four cuttings starting about May 26 as weather and crop maturity permitted with the wilted silage stored in a bunker silo. The average yield over 25 climate years was 13.6 t DM/ha. Corn silage harvest started on or after September 1 as weather and crop maturity permitted using a roller processor on a chopper. The corn silage was stored in a bunker silo, and the average yield was 15.7 t DM/ha. Corn grain harvest started around October 15 with the corn harvested and stored as dried (15% moisture) grain. The average yield was 7.0 t DM/ha. Grass was harvested in 2 cuttings starting around May 20th. The grass was baled as dry hay with an average yield of 6.0 t DM/ha.

2.2.2. 150-cow farm in Wisconsin

The 150-cow farm consisted of 150 milk cows (lactating and non-lactating Holstein) and 130 replacement heifers (64 older heifers and 66 younger heifers; 40% replacement rate). Milk production averaged 10,134 kg/cow/year corrected to 4% fat and 3.3% protein. Animals were fed a TMR consisting of alfalfa silage, corn silage, oat silage, high-moisture corn grain, soybean meal and expeller’s soybean meal. The diet CP content for lactating cows was 17%. All animals were fed P at 15% above NRC (2001) requirements. The milk cows were housed in naturally ventilated free stall barns with sand bedding. Replacement heifers were housed in a bedded pack barn with straw/corn stalk bedding. The bedded pack barn served as storage for the manure, which was removed every 6 months and handled as a solid. Milk cow manure was handled as a slurry (8–10% DM) that was stored in a tank for about 6 months. Manure was broadcast applied to crop land in the spring and fall with no incorporation into the soil.

The farm cultivated 130 ha of cropland. The cropland was gently sloping and had a high soil P level. The soil was a Plano silt loam with 22% clay, 45.5% silt, 32.5% sand, and a water holding capacity of 185 mm. Three crops grown were corn, alfalfa and oats. All forage and grain needed were produced on the farm. Corn (105 day corn variety) was grown on 67 ha of the total cropland. Corn fields received 70% of the manure plus 60 kg N/ha of fertilizer applied at planting (SI Table 5). No other fertilizer or lime was applied to the corn crop. Alfalfa was grown on 63 ha in a 4-year stand. While alfalfa fields were not utilized they were amended with an average of 1.3 t/ha/yr of lime. Oats were grown on 62 ha of the total cropland. The oats received 30% of the manure and were seeded in spring with the alfalfa. Field management practices were characterized as conventional till (chisel plow, disk, field cultivator, planting) (SI Table 6). Alfalfa silage was harvested in four cuttings starting around May 28. The wilted silage was stored in a bunker silo. Average annual yield was 10.4 t DM/ha. Corn silage harvest started around September 5 as weather and crop maturity permitted, using a roller processor on a chopper. The corn silage was stored in a bunker silo and the average yield was 16.3 t DM/ha. Remaining corn was harvested as high moisture grain beginning around October 21 with an average yield of 8.1 t DM/ha. The corn stalks remaining after grain harvest were used for bedding in the heifer barn. Oat harvest started around June 26 with an average silage yield of 7.3 t DM/ha.

2.2.3. Location-specific historical weather data

Historical weather data representative of the NY farm site (Skaneateles) was obtained from the North American Regional Reanalysis (http://www.esrl.noaa.gov/psd/data/gridded/data.narr.html). This provided daily maximum and minimum temperature, precipitation, wind speed, and relative humidity while solar radiation was estimated using the APEX model (Williams et al., 2012; version 0806). Historical weather data for the WI farm site (Arlington) was downloaded from UW Extension Ag Weather (http://agwx.soils.wisc.edu/ uwex_agwx/awon).

2.3. Beneficial Management Practices (BMPs)

Farm-specific BMPs were identified and characterized for three farm components, i.e. “Feed”, “Manure Management” and “Field management”. The BMPs were developed based on a BMP definition workshop with specialists of each farm component and in consultation with external experts. Each is expected or known to reduce direct and/or indirect GHG emissions. We briefly describe the included BMPs here (see Table 2). We refer to the SI for more detailed information on the BMP implementation in IFSM (SI Tables 3 & 5: fertilizer and manure application schedule; SI Table 4 & 6: Tillage and planting parameters for baseline and field BMPs, SI Table 7&11: Crop hectares, milk production, crop yield and feed purchases).

We considered 5 individual dietary mitigation strategies: 50% forage rations, high NDF digestibility, high feed efficiency, high fat, and reduced protein (14% CP) (Table 2). These dietary mitigation strategies focus on reducing absolute emissions of CH₄ and urinary urea N excretion through diet manipulation, and/or on increasing animal productivity, which reduces relative CH₄ emissions and nutrient losses per kg milk produced, but may increase absolute emissions per cow per day (see also reviews by Hristov et al., 2013) and (Knapp et al., 2014). Other strategies to reduce enteric CH₄ emission have been proposed, including the addition of electron receptors (nitrate), ionophores and tannins (Hristov et al., 2013). Given that the effect of these dietary strategies remain to be fully mechanistically understood and quantified, they were not included in this modelling study.

We developed farm-size specific manure management BMPs as manure storage systems and management practices vary substantially with farm size (Aguirre-Villegas and Larson, 2017). For the 1500-cow farm, we considered 4 manure management BMPs: sealed with flare, solid-liquid separation (SLS), anaerobic digestion (AD) and SLS + AD (Table 2). For the 150-cow farm, 3 manure management BMPs were considered: free-stall for heifers, covered storage, and sealed with flare (Table 2).

Six field BMPs were considered: cover crop, double crop, no-till, summer application of manure, same day incorporation of land applied manure, and no-till with injection of manure. Cover crops, rye double crops and no-till management practices have limited potential to mitigate GHG emissions (e.g. van Kessel et al., 2013; Basche et al., 2014; Parkin et al., 2016; Powelson et al., 2014), however these practices have been shown to reduce NOₓ leaching and P losses through soil erosion (Parkin et al., 2016) and were included to mitigate nutrient losses from the field.

2.4. Model simulation: Integrated Farm System Model (IFSM)

The Integrated Farm System Model (IFSM4.3) is a well-established, process-based, whole-farm model that can be used to assess and compare the environmental and economic sustainability of farming systems (Rotz et al., 2016a). The model is described in detail in Rotz et al. (2016a) (http://www.ars.usda.gov/Main/docs.htm?docid = 8519/) and is only briefly described here.

The IFSM simulates crop production, feed use, and the return of manure nutrients back to the land for 25 years of daily weather on a crop, dairy, or beef farm (Rotz et al., 2016a). Growth and development of crops (grass, corn, soybean, and small grain crops) are predicted for each day based upon soil water and N availability, ambient temperature, and solar radiation. Simulated tillage, planting, harvest, storage, and feeding operations predict resource use, timeliness of operations, crop losses, and nutritive quality of feeds. Feed allocation and animal responses are related to the nutrient contents of available feeds and the nutrient requirements of the animal groups (replacement heifers, non-lactating and lactating cows) making up the herd. The quantity and nutrient contents of the manure produced are a function of the feeds consumed and herd characteristics.

IFSM tracks nutrient flows to predict losses to the environment and.
potential accumulation in the soil (Rotz et al., 2016a). Losses include ammonia (NH₃) volatilization, denitrification (N₂O, N₂) and leaching losses of N (NO₃⁻), erosion of sediment and nutrients (N and P) across the farm boundaries, and the runoff of dissolved P and N. Carbon dioxide, CH₄, and N₂O emissions are tracked from crop, animal, and manure sources and sinks.

IFSM simulations of GHG emissions and nutrient losses, and simulated crop yields and feed production, have been evaluated in numerous studies. Model predictions of GHG emissions and nutrient losses were evaluated by Chianese et al. (2009a, 2009b, 2009c) and (Rotz et al., 2014). Some of the most comprehensive evaluations of crop yield across multiple years of weather were done by Rotz et al. (2001, 2002). Predicted yield and feed production have also been evaluated for an actual, commercial farm in New York by Rotz and Hafner (2011). This commercial farm was originally used as the basis for setting up the New York farm in the current study. In previous work by Velm an et al. (2017) this same farm was used with further calibration and evaluation of crop production and feeding of the animals (although not specifically documented in the paper).

IFSM includes a cradle-to-farm gate partial life cycle assessment module to determine annual C and reactive N footprints per unit of farm product produced. The C footprint is predicted from net GHG emissions in CO₂ equivalent units, where a unit of CH₄ is equivalent to 28 units of CO₂ and N₂O is equivalent to 265 CO₂ units in global warming potential (GWP-100) (Myhre et al., 2013). The reactive N footprint is predicted from the total reactive N losses (any form of N other than N₂). Some N containing gases, such as N₂O and NH₃, contribute to the reactive N footprint as well as the C footprint. Because 1 mol of N₂O or NH₃ can contribute to climate change as well as to environmental impacts associated with reactive N emissions (e.g. Galloway et al., 2003). For dairy farms, footprints are determined as the sum of reactive N losses or GHG emissions associated with dairy farming and pre-farm sources, minus allocations to co-products (calves and culled cows sold), divided by the amount of fat and protein corrected milk produced (Rotz et al., 2016a). The IFSM uses a biophysical allocation procedure to allocate resource use and emissions to the primary product (milk) and co-products (calves and cull cows sold) (Rotz et al., 2016a). For calves and cull cows sold, an allocation factor is calculated based upon the physiological feed requirements of the animal to produce milk and meat (IDF, 2010). For the 1500-cow farm, part of the manure is exported from the farm. The IFSM allocates post-farm gas emissions from exported manure to the system receiving the manure (Rotz et al., 2016a).

However, when manure solids are composted on-farm, as is the case in our manure- and field-BMPs, emissions associated with composting and on-farm handling are included in the simulation and attributed to the farm (Rotz et al., 2016a). Once the compost leaves the farm for use in landscaping, etc. any further emissions and the carbon in that compost are not associated with the farm; they are allocated to the other uses.

In addition to the environmental footprint, IFSM includes an economic module to determine the net return or profit potential for the farm (Rotz et al., 2016a). A whole-farm budget is used where the annual production cost for each simulated year is compared to the annual revenue (income received for milk, animal and excess feed sales) to predict the net return to management. Production costs include amortized fixed costs associated with capital investments in machinery and facilities, and variable costs associated with resource use for crop and animal production as well as service flows from durable assets (Rotz et al., 2016a). Averaging the annual net returns over the 25 simulated years (with all relative prices and values in current dollars) provides a metric to compare different production systems in terms of long term profitability. It should be noted that while the net return is a good metric to compare production systems or BMP scenarios in terms of potential, long-term profitability, it is not necessarily a good representation of the future profit of a specific production system as the impacts of income taxes and other government payments and future regulations that may affect the profitability of the business are not included.

### 2.5. Comparison of BMPs

We used five metrics to compare the BMPs to each other and to the baseline: C footprint, reactive N footprint, total P loss, milk production and net return. We therefore obtained milk production, total animal weight leaving the farm, net returns, emissions of individual GHGs (e.g. enteric CH₄, manure storage N₂O etc.) and nutrient losses per farm source from IFSM. The individual GHG emissions were converted to CO₂-equivalents, summed up, and allocated to produced milk according to IFSM rules (see Section 2.4). This calculated footprint was added to the footprints associated with resource production, fuel combustion (anthropogenic CO₂) and indirect N₂O emissions, which were directly obtained from IFSM. The total reactive N footprint was calculated in a similar fashion (with the footprint associated with resource production and fuel combustion directly obtained from IFSM). IFSM does not directly quantify a P footprint. We therefore collected pathway-specific

### Table 3

1500-cow farm: Environmental and economic performances for all scenarios, i.e. baseline, individual BMPs and the two BMP packages for feed mitigation (see Section 3.2.6) and whole-farm mitigation (see Section 3.5). Standard deviation represents the annual variability over 25 years of weather.

<table>
<thead>
<tr>
<th>Scenario (baseline or BMP)</th>
<th>C footprint (kg CO₂ eq. kg milk)</th>
<th>Reactive N footprint (g N /kg milk)</th>
<th>P loss (mg P /kg milk)</th>
<th>Net return ($ /cow)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>St. dev.</td>
<td>Value</td>
<td>St. dev.</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.99</td>
<td>0.03</td>
<td>11.8</td>
<td>1.2</td>
</tr>
<tr>
<td>50% forage rations</td>
<td>0.91</td>
<td>0.03</td>
<td>11.5</td>
<td>1.3</td>
</tr>
<tr>
<td>High feed efficiency</td>
<td>0.92</td>
<td>0.02</td>
<td>10.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Reduced protein</td>
<td>0.95</td>
<td>0.03</td>
<td>11.0</td>
<td>1.1</td>
</tr>
<tr>
<td>High NDF digestibility</td>
<td>0.97</td>
<td>0.03</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>High fat</td>
<td>0.99</td>
<td>0.03</td>
<td>11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Feed mitigation</td>
<td>0.79</td>
<td>0.03</td>
<td>8.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Sealed with flare</td>
<td>0.79</td>
<td>0.02</td>
<td>11.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Separation and digestion</td>
<td>0.84</td>
<td>0.02</td>
<td>11.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Digestion</td>
<td>0.84</td>
<td>0.02</td>
<td>12.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Separation</td>
<td>0.95</td>
<td>0.02</td>
<td>11.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Rye double crop</td>
<td>0.98</td>
<td>0.02</td>
<td>11.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Cover crop</td>
<td>0.99</td>
<td>0.02</td>
<td>11.0</td>
<td>1.1</td>
</tr>
<tr>
<td>No-till with injection</td>
<td>1.0</td>
<td>0.02</td>
<td>10.5</td>
<td>1.8</td>
</tr>
<tr>
<td>No-till</td>
<td>1.0</td>
<td>0.02</td>
<td>12.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Incorporated same day</td>
<td>0.90</td>
<td>0.02</td>
<td>11.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Summer application</td>
<td>0.96</td>
<td>0.02</td>
<td>11.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Whole-farm mitigation</td>
<td>0.64</td>
<td>0.02</td>
<td>7.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>
predictions of P losses by IFSM, summed them up, and allocated the total P losses to milk production. This provides the total, P loss, but excludes the contributions of pre-farm sources.

To determine the BMP efficacy, we calculated the percentage reduction in footprint and total P loss ((1 - FPCM_BMP / FPCM_Baseline) × 100%), the percentage change in milk production ((Milk_BMP / Milk_Baseline - 1) × 100%), and the percentage change in net return ((Net return_BMP / Net return_Baseline - 1) × 100%), relative to the baseline scenario. We identified the best performing individual feed BMPs, in terms of C footprint reduction, to establish a combined feed mitigation strategy. Similarly, we identified desirable individual BMPs per farm component to establish a whole-farm mitigation strategy.

2.6. Model evaluation

A complete evaluation of whole-farm model predictions for all scenarios is impossible as no empirical datasets are available that measure emissions and losses of relevant compounds for all farm components in all scenarios for both farms. To provide some evaluation, we compare predicted %changes by IFSM for a specific BMP to empirical, literature-derived data for specific emissions and farm components (such as the cow). Additionally, we use an animal-scale model (CNCP6.1.54), a field model (EPICv1102) and a biogeochemical farm model (Manure-DNDC) to contextualize IFSM predictions of milk production and environmental impacts (per farm-component) for the whole farm mitigation scenario. A detailed description of the models and the contextualization procedure is provided in Section 1 of the Supporting Information.

3. Results and discussion

The milk production and environmental and economic performance indicators for the baseline scenario and the individual BMPs for both farms are provided in Table 3 and Table 4 and visualized in Figs. 1–3. We present and discuss the results of the 1500-cow farm and the 150-cow farm, respectively. The average crop yields, as well as GHG emissions and nutrient losses per hectare, are presented in the SI, in Table 7 & 10 and Table 11 & 14, respectively.

3.1. Baseline farms

IFSM predicted a baseline C footprint of 0.99 kg CO2eq. / kg milk produced and 1.1 kg CO2eq. / kg milk produced for the 1500-cow farm and the 150-cow farm, respectively (Fig. 2A, Fig. 3A). These predicted footprints are comparable to the farm-gate C footprints of 1.0 kg CO2eq. / kg FPCM and 1.23 kg CO2eq. / kg FPCM (90% CI: 1.1–1.45 kg CO2eq. / kg FPCM) reported by Gerber et al. (2010) and Thoma et al. (2013) for the average US dairy farm. The slightly higher footprint of the 150-cow farm results from the bedded-pack barn, which has higher CH4 emissions per kg milk produced than the free-stall barn used to house heifers on the 1500-cow farm.

Consistent with previous LCA studies (Thoma et al., 2013, O’Brien et al., 2014), we find that enteric CH4 is the predominant contributor to the C footprint (~45% contribution), followed by CH4 emissions from manure (~16% contribution), and GHG emissions associated with pre-farm sources (~13% contribution).

Similar to the C footprint, the reactive N footprint and P loss are slightly higher for the 150-cow farm baseline in comparison to the 1500-cow farm baseline (Table 3, Table 4). The predicted baseline reactive N footprints are 11.8 g N / kg milk produced and 13.8 g N / kg milk produced for the 150-cow farm and 150-cow farm, respectively (Fig. 2B, Fig. 3B). Approximately half of this footprint is attributable to NH3 volatilization and another ~30% is attributable to leaching losses.

The predicted baseline P loss is 47 mg P lost / kg milk produced and 107 mg P lost / kg milk produced for the 1500-cow farm and the 150-cow farm, respectively (Figs. 2C, 3C). Run-off of sediment-bound P is the predominant loss pathway for both farms. The predicted difference in P loss is partly attributable to the export of manure solids from the 1500-cow farm. As a result, less manure is applied on the field (23 kg/ha vs. 33 kg/ha for the 1500-cow farm and 150-cow farm, respectively), resulting in lower P losses. Also, P losses are influenced by climate and soil characteristics. These factors differ between the two farm locations, which can result in differences in P losses as well.

Consistent with a larger milk production, the net return per cow of the 150-cow farm is greater than the net return for the 1500-cow farm, amounting to 1127 $/cow and 906 $/cow for the 150-cow farm and the 1500-cow farm, respectively (Figs. 2D, 3D).

3.2. Feed

Most individual feed BMPs were predicted to reduce the C footprint and simultaneously reduce the reactive N footprint with predicted reductions ranging from 2% to 12% and 1% to 15%, for the C footprint and the reactive N footprint, respectively (Figs. 2A & B, 3A & B). In contrast, individual feed BMPs were predicted to have mixed effects on the P loss (2% decrease to 12% increase) and on the farm profit (9%
substantial (~19%) reduction in absolute enteric CH4 emissions. This potential of the predicted reduction potential of approximately 11%. The reduction diet (3.2.1. 50% forage centrate feeding, but comparable to the 17% reduction in enteric CH4 production of 15% suggested by Knapp et al. (2014) for increased concentration feeding, but comparable to the 17% reduction in enteric CH4 emissions per cow per day reported by Aguerre et al. (2011) who decreased the forage-to-concentrate ratio from 68:32 to 47:53 using common feeds of the US Midwest. While the ’50% forage ration BMP is the best performing BMP in terms of C footprint reduction, the effect of this BMP on the reactive N footprint, P loss and the net return, is mixed. For the reactive N footprint, a slight reduction (3%) was predicted for the 1500-cow farm. However, a 7% increase in N footprint was predicted for the 150-cow farm, which was predominantly caused by a predicted 40% increase in N leaching. Reducing the forage fraction in the diet increased total P loss at the 1500-cow farm (12%) and slightly decreased total P loss at the 150-cow farm (1%). For the 1500-cow farm, the predicted increase in P loss resulted from the increased fraction of corn land on the farm, which, in turn, caused an increase in sediment-bound P losses (15%). For the 150-cow farm, the potential increase in sediment-bound P loss was neutralized by a decrease in excreted and land applied P in manure. For both farms, the net return was simulated to decrease (~7.5%) as a result of an increased requirement of fertilizer N for the added fraction of corn grain land.

3.2.2. High feed efficiency
The second most effective BMP in terms of C footprint reduction was the BMP ‘high feed efficiency’ with a predicted reduction potential of approximately 7%. This BMP simultaneously reduced the reactive N footprint and the P loss by approximately 9% and 8%, and substantially increased the net return of both farms by approximately 27%. Increasing the feed efficiency by 10% was predicted to increase milk production by 7.5% (Fig. 1), thus decreasing the GHG emissions and nutrient losses per kg of milk produced and increasing farm profits. In addition to increasing milk production, increasing the feed efficiency reduced annual feed purchases, which further reduced the reactive N footprint and increased the net return for the farm (Figs. 2D, 3D).

The predicted increase in milk production is consistent with Bell et al. (2011), who reported a 8.4% difference in feed efficiency, and milk production, between control Holstein-Friesian dairy cows, with a milk yield close to the UK average, and selected, high-producing cows. Similarly, van Middelaar et al. (2014) reported a genetic standard deviation for milk yield of Dutch Holstein-Friesian dairy cows of 687 kg/year, which corresponds to a 7.8% increase in milk production (from an average of 8758 kg/yr to 9445 kg/yr with no changes in fat and protein fractions). It should be mentioned here that the IFSM is a process-based model, which simulates milk production based on, among others, feed quality, rumen fill, rumen passage rate and maintenance requirements of the animal. There is thus no linear relationship between milk production and feed intake in IFSM simulations. A 10% increase in feed efficiency, as used here, can thus result in a lower increase in milk production.

3.2.3. Reduced protein
Although the BMP “reduced protein” was predominantly included to reduce overall reactive N losses, this BMP was predicted to provide modest reductions (~3.5% reduction) in the C footprint as well. Decreasing the protein fraction in the diet decreased the C footprint associated with feed purchases (~5%) and the C footprint associated with enteric CH4 emissions (~3%). The reduction in enteric CH4 was not expected, as reducing dietary protein does not decrease enteric CH4 emissions per se, but may result from some unavoidable small changes in the diet. Compared to the baseline scenario, the corn grain fraction of the diet was slightly increased in the ‘reduced protein’ BMP, which could reduce enteric CH4 emissions (Knapp et al., 2014).

In terms of reactive N footprint, reducing the protein content in the rations to 14% was predicted to be the most effective strategy to reduce this footprint. Consistent with expectations (e.g. Powell et al. (2008); Mieselbrook et al. (2005); Montes et al. (2013); Bougouin et al. (2016)), reducing dietary protein content substantially reduced the overall NH3 emission intensity on the farm (> 20% reduction). In addition, a substantial reduction in the reactive N footprint associated with resource production (~27% reduction) was predicted, owing to a substantial reduction in soybean meal purchases (44%). Due to this predicted decrease in annual feed purchases, this BMP also increased the net return for the farm (Figs. 2D, 3D). There is, however, a potential trade-off in terms of P loss: the P loss at both farms was predicted to increase (~7%), mainly due to an increased proportion of corn grain land and a consequential increase in sediment-bound P loss.

3.2.4. High NDF digestibility
Despite a predicted 4.9% increase in milk production, increasing NDF digestibility by 2% had a modest potential to reduce the C footprint with a reduction of 2% for both farms. Consistent with expectations (e.g. Knapp et al. (2014)), increasing NDF digestibility increased the predicted DMI, which, in turn, resulted in a slight increase in absolute CH4 emissions from the cow and from the manure storage, and
an increase in the pre-farm C footprint due to increased feed purchases. These predicted increases in absolute CH₄ emissions and the absolute C footprint associated with pre-chain sources offset part of the C footprint mitigation potential for 'high NDF'. This emphasizes the need to perform a whole-farm analysis, including pre-chain sources, to assess the GHG mitigation potential of BMPs.

Increasing NDF digestibility had a modest, but positive, effect on the reactive N footprint, and a negligible impact on P loss (Figs. 2B & C, 3B & C). The predicted positive effect of an increase in milk production was partly negated by the predicted increase in DMI, which resulted in an increase in manure nutrient excretion and a consequential increase in absolute nutrient losses. The increase in milk production did, however, result in a substantial increase in farm profits (12% increase) (Figs. 2D, 3D).

3.2.5. High fat

Dietary fat supplementation has been proposed as a promising strategy to mitigate enteric CH₄ emissions (e.g. Grainger and
Beauchemin, 2011; Knapp et al., 2014). IFSM, however, predicted a negligible benefit from increasing dietary fat concentrations on the whole farm C footprint. The predicted benefits, i.e. a 2.5% increase in milk production (Fig. 1) and a consequential decrease in enteric CH4 emissions per kg milk produced, were fully negated by a predicted increase of ~5% in the pre-farm footprint due to fat purchases, again illustrating the need for a holistic assessment of farm-component specific BMPs.

Fig. 3. Carbon Footprint (A), Reactive Nitrogen Footprint (B), Phosphorus Losses (C) and Net Return (D) for the 150-cow farm in Wisconsin showing the contribution of individual flows to the total footprint and total P loss. The whole-farm mitigation strategy consists of 5 individual BMPs: feed mitigation (see Section 3.2.6), covered manure storage with flare, free-stall barn for heifers, no-till system with subsurface injection of manure and summer application of manure (see Section 3.5).

Beauchemin, 2011; Knapp et al., 2014). IFSM, however, predicted a negligible benefit from increasing dietary fat concentrations on the whole farm C footprint. The predicted benefits, i.e. a 2.5% increase in milk production (Fig. 1) and a consequential decrease in enteric CH4 emissions per kg milk produced, were fully negated by a predicted increase of ~5% in the pre-farm footprint due to fat purchases, again illustrating the need for a holistic assessment of farm-component specific BMPs.

Modest, positive effects of the BMP ‘high fat’ were predicted for the reactive N footprint, P loss, and the net return. The predicted increase milk production resulted in reduced environmental impacts per kg milk produced and an increase in the net return for the farm (Figs. 2B–D, 3B–D).

3.2.6. Feed mitigation strategy
We developed a combined mitigation strategy based on the most
promising individual feed BMPs in terms of C footprint reduction, i.e. '50% forage', 'high NDF digestibility', 'high feed efficiency', and 'reduced protein'. The combined “feed mitigation” strategy increased milk production (~11%) and farm profitability (~37%), and reduced the C footprint (~22%) and the reactive N footprint (1500-cow farm: ~25% reduction, 150-cow farm: 10% reduction). Mixed effects were, however, predicted for P loss (Figs. 2C, 3C): a ~10% increase in P loss was predicted for the 1500-cow farm and a 6% decrease was predicted for the 150-cow farm.

3.2.7. Summary

Overall, our assessment of individual BMPs shows that dietary manipulation and increasing the feed conversion efficiency present important opportunities to reduce the overall environmental impact of a unit of milk produced through increasing milk production, by reducing enteric CH4 emission and urinary N losses, and/or by reducing the C and reactive N footprint associated with feed purchases (Figs. 2, 3). Trade-offs can, however, occur between GHG mitigation and P losses and farm profitability, when the corn grain fraction in the diet is increased.

3.3. Manure

All considered manure BMPs were predicted to reduce the C footprint (Figs. 2A, 3A). With exception of the BMP ‘free-stall for heifers’, the overall effect of manure BMPs on the reactive N footprint and P loss was small and variable (Figs. 2B&C, 3B&C). Most individual manure BMPs were on their own - not cost-effective (Figs. 2D, 3D).

3.3.1. Sealed with flare (150-cow and 1500-cow farm)

For both farms, the BMP ‘sealed with flare’ was the most effective BMP in terms of C footprint reduction with a predicted reduction potential of 19% and 12% for the 1500-cow farm and the 150-cow farm, respectively. The reduction in C footprint was achieved by a 99% reduction in CH4 emissions from manure storage. This reduction in CH4 emissions from manure storage is < 100% as IFSM assumes a CH4 leakage rate of 1% from this system. The 99% effectiveness of the flare, and the consequential 99% reduction in CH4 emissions, may however, be an overestimation. A pilot study from (Wightman and Woodbury, 2016) on 3 dairy farms in New York with separated-liquid manure storage retrofitted with a cover and flare suggested an annual flare effectiveness of 81%. In the winter months the flare may not be used, resulting in a lower annual average effectiveness than 100% (Wightman and Woodbury, 2016), and higher annual average CH4 emission than predicted.

The BMP ‘sealed with flare’ had negligible effects on the reactive N footprint and P loss. This BMP was, however, predicted to reduce farm profits of the 1500-cow farm and the 150-cow farm by 8% and 4%, respectively. This decrease in farm profits results from the relatively high initial investment costs associated with implementation of a flare and sealing the manure storage with small economic benefit through improved nutrient cycling.

3.3.2. Anaerobic digestion (with or without SLS) (1500-cow farm)

For the 1500-cow farm, the BMPs ‘SLS + AD’ and ‘AD’ were found to be the second most effective BMPs in terms of C footprint reduction potential. For both BMPs, a C footprint reduction of 16% was predicted (Figs. 2A, 3A). The anaerobic digester converts CH4 from manure into energy, thus substantially reducing the CH4 emissions from manure storage (71% reduction). This reduction potential is slightly lower than the reduction potential predicted for the BMP ‘sealed with flare’ (i.e. 71% versus 99%). The difference in CH4 reduction potential between AD (with or without SLS) and ‘sealed with flare’ results from a difference in operating efficiency: a CH4 leakage rate of 1% was assumed for both systems, and this releases much more CH4 from a digester where CH4 is being generated. The 1% biogas leakage rate used for the AD is in the lower end of the range (0.40–3.28%) found by Liebetrau et al. (2013) for 10 biogas plants in Germany. Flesch et al. (2011) also determined an average fugitive emission rate corresponding to 3.1% of the CH4 gas production rate during normal operations of a Canadian anaerobic digester. This may suggest that the GHG mitigation potentials of the BMPs AD and ‘SLS + AD’ were overestimated. However, according to Liebetrau et al. (2013), near zero fugitive emissions can be obtained when leaks and malfunctions are eliminated, implying that efficient operation of the AD is key to maximize GHG mitigation potential.

The BMPs ‘SLS + AD’ and ‘AD’ had variable effects on the reactive N footprint: ‘SLS + AD’ was predicted to reduce the reactive N footprint by 3%, whereas AD alone was predicted to increase the reactive N footprint by 3%. Anaerobic digestion increases the total ammoniacal N (NH3 + NH4+) content of manure due to the mineralization of organic N. As a result, IFSM predicted an increase in cumulative NH3-N emissions (9% increase) for the BMP ‘AD’, which is consistent with empirical observations (Holly et al., 2017; Neeracal et al., 2015). Combining AD and SLS was predicted to reduce NH3-N emission following land application (21%) due to the greater infiltration of liquid manure into the soil surface. This predicted reduction is consistent with expectations (Rotz, 2004; Holly et al., 2017) and was sufficient to offset the predicted increase in NH3-N emissions from manure storage (49%), resulting in a small overall mitigation potential for AD + SLS.

The BMPs ‘SLS + AD’ and ‘AD’ were predicted to have a small (1%), but positive effect on P loss. Similar to the BMP ‘sealed with flare’, implementation of these BMPs was predicted to be not cost-effective. A decrease in net return (3% - 8% decrease) was predicted for the BMPs SLS + AD, AD and sealed with flare. These decreases resulted from the relatively high initial investment costs. Although AD does produce gas and electricity used on the farm, this was not sufficient to negate the high initial investment.

3.3.3. Solids-liquid separation (SLS) (1500-cow farm)

The BMP ‘separation’ was predicted to have a modest potential to reduce the C footprint. The 4% reduction in C footprint was predominantly achieved by reducing CH4 emissions from manure storage (21% reduction). This reduction is consistent with, but lower than the 46% reduction in CH4 emission determined by Holly et al. (2017) for storage of separated solids + liquids in comparison to raw manure. The difference may result from a difference in separation efficiency, with lower CH4 emissions associated with more efficient separation.

Similar to the C footprint, a modest (5%) reduction potential was predicted for the reactive N footprint (Figs. 2B, 3B). Consistent with expectations (Rotz, 2004; Amon et al., 2006; Hou et al., 2015; Holly et al., 2017). SLS substantially reduced NH3-N emission following land application of manure. The predicted reduction in NH3-N volatilization (29%) is in the range of empirically determined reductions (0% - 59%) (Amon et al., 2006; Hou et al., 2015, Holly et al., 2017). The potential mitigation of reactive N footprint was, however, largely negated by a predicted increase in NH3-N emissions from manure storage (40%) and an increase in N leaching losses (9%). The predicted increase in NH3-N emissions from manure storage may result from composting of the manure. Part of the manure solids were used as bedding material, and were processed through composting to reduce pathogens, which can result in relatively high N emissions (up to 40% of initial N) (Rotz, 2004). The increase in N leaching can be explained by the increase in soil N resulting from a decrease in N loss via NH3 volatilization following manure land application.

The BMP “separation” had a negligible impact on P loss. A modest, positive effect (2% increase) on the farm profit was, however predicted. The predicted storage costs were similar to the baseline scenario and the use of manure solids for bedding eliminated the need to buy bedding material, resulting in a larger profit in comparison to the baseline.
3.3.4. Free-stall for heifers (150-cow farm)

Replacing the bedded-pack barn with a free-stall for the heifers reduced the C footprint, the reactive N footprint and the P loss of the 150-cow farm by 11%, 12% and 17%, respectively. This BMP was, however, predicted to decrease the net return by 4%.

In terms of C footprint reduction, the BMP “free-stall for heifers” was the second most effective BMP. Replacing the bedded-pack barn with a free-stall substantially reduced CH4 emission (95%) from manure on the barn floor, although the overall C footprint mitigation potential was partly offset by a predicted 66% increase in CH4 emissions from manure storage. The reduction in reactive N footprint was achieved through a predicted 22% reduction in field NH3-N emissions and, to a lesser extent, through a 100% reduction in gaseous N losses (NO + N2O) from the barn. The reduction in field NH3-N emission primarily resulted from greater infiltration of liquid manure into the soil surface and partly from a reduction in manure N applied on the field (less added bedding material). A faster removal of manure from the barn floor in a free-stall barn in comparison to the bedded-pack barn reduces the potential for nitrification/denitrification processes to occur, thus reducing gaseous N losses from the barn.

This BMP was also predicted to reduce total P loss by 17% due to a decrease in run-off of sediment-bound P. This decrease in run-off resulted from greater infiltration of the liquid manure into the soil and greater soil surface cover by not removing stover for bedding use. In contrast to the predicted positive effect on the environmental impact indicators, replacing the bedded pack barn with a free-stall decreased the net return by 4%, due to an increase in barn and manure storage costs.

3.3.5. Covered storage (150-cow farm)

Consistent with expectations (e.g. Montes et al., 2013), covering the manure storage reduced the C footprint (7% reduction) on the 150-cow farm. This reduction was achieved through a reduction in CH4 (45%) and N2O (100%) emissions from the manure storage. Since the cover is semi-permeable, CH4 emissions were not fully negated. N2O emissions were fully negated, as the cover eliminates the optimal conditions for nitrification and denitrification at and just below the crust’s surface (Montes et al., 2013), thus greatly reducing the production of N2O. Covering the storage had a small, but negative, effect on the reactive N footprint and a negligible effect on P loss. This BMP was also predicted to reduce farm profits by 2% due to the high initial investment costs.

3.3.6. Summary

Substantial reductions in C footprint can be obtained with individual manure storage and handling interventions (1500 cows: 4–20% reduction; 150 cows: 7–12% reduction). Because enteric CH4 emissions dominate the whole-farm C footprint, the effect of the reduction of manure storage CH4 emissions on the whole-farm C footprint is substantially less than the reduction potential for the manure management component on its own. Trade-offs can, however, occur between GHG mitigation and farm profitability.

3.4. Field

Our results show that field BMPs can substantially reduce the reactive N footprint (0–19% reduction) and on-farm P losses (1–47% reduction). In addition, most field BMPs were predicted to be cost-effective, although the economic benefit of implementing these BMPs was small (1%–6%) or zero (Figs. 2D, 3D). For either farm, the field BMPs were found to have no or minimal potential (0–3% reduction) for mitigating the C footprint, however, there were also no trade-offs observed (Figs. 2A, 3A).

3.4.1. Cover crop and double crop

The BMPs ‘cover crop’ and ‘rye double crop’ were predicted to reduce the reactive N footprint and P loss on both farms. The reactive N footprint reduction potential is, however, farm-specific. For the 1500-cow farm, the ‘cover crop’ was predicted to be the second best performing BMP in terms of reactive N footprint reduction. An 18% reduction in N leaching losses was predicted, which resulted in a 7% reduction in the reactive N footprint for the 1500-cow farm. For the 150-cow farm, the ‘rye double crop’ was predicted to be the second most effective BMP (13% reduction), also chiefly through a 42% reduction in N leaching losses. The predicted decrease in N leaching losses with cover cropping is consistent with the 13% to 70% range in N leaching loss reductions found in field studies (Tonitto et al., 2006; Brandi-Dohn et al., 1997; Krueger et al., 2012; Stock et al., 2004). The difference in effectiveness of the cover crop versus rye double crop for the 1500-cow farm and the 150-cow farm seems to be related to scenario set-up. For the 1500-cow farm, the N fertilizer application rate for the cover crop was reduced, which reduced N losses from the field, thus reducing the reactive N footprint. For the rye double crop, N fertilizer application rate was increased for corn, to compensate for a reduction in manure N application to the corn field (30% of collected manure is now applied and potentially taken up by the rye). This added N partially negates the rye double crop’s benefits. For the 150-cow farm, the rye double crop performs better than the cover crop in terms of reactive N mitigation potential, primarily because N leaching losses were predicted to be lower for the rye double crop than for the cover crop.

The BMPs ‘cover crop’ and ‘rye double crop’ were particularly effective BMPs in reducing P loss with reduction potentials ranging from 13% to 46% (Figs. 2C, 3C). In agreement with other studies (e.g. Dodd and Sharpley, 2016), both cover cropping and double cropping were predicted to reduce run-off of sediment-bound P (31% - 54% reduction).

These BMPs, were, however, not always cost-effective. The ‘cover crop’ reduced the net return by ~3%, primarily because of increased seed and planting costs with little economic return. In the ‘cover crop’ scenario, corn grain land was increased by 2% in comparison to the baseline to compensate for a loss in grain yield due to the loss of available soil moisture taken up by the cover crop prior to corn planting. The ‘rye double crop’ was predicted to increase the net return of the 1500-cow farm by 4%, primarily through a reduction of purchased feed. For the ‘rye double crop’, corn grain land was also increased to compensate for a small loss in corn grain yield, however, the added production costs were fully negated by the reduced costs for purchased feed through the use of the rye forage. For the 150-cow farm, the ‘rye double crop’ was predicted to reduce farm profits by 2%, as the increased production costs for establishing and harvesting the double crop were not fully offset by the saving in purchased feed.
for the 1500-cow farm and the 150-cow farm, respectively. The predicted reductions in P loss are consistent with, although lower than, the reduction potentials determined in field studies (~80% reduction) (Sharpley and Smith, 1991; McDowell and McGregor, 1984). To a lesser extent, the P loss mitigation potential of ‘no-till with injection’ is also associated with predicted reductions in run-off of dissolved P. IFSM predicted a 49% and 75% reduction in dissolved P loss for the 1500-cow farm and the 150-cow farm, respectively, which is consistent with empirically determined mitigation potentials (71%–94%) (Maguire et al., 2011; Jokela et al., 2016).

No-till with injection had a modest, positive effect (3% increase) on the net return of both farms. No-till with injection reduced the requirement for pre-planting N fertilizer application on corn land, which, in turn, reduced the need to purchase fertilizer and increased farm profit.

### 3.4.3. No-till

The effect of the BMP ‘no-till’ on the reactive N footprint and P loss was farm specific and variable. For the 1500-cow farm, ‘no till’ increased the reactive N footprint by 3% and reduced P loss by 43%. For the 150-cow farm, a negligible impact of ‘no till’ was predicted on the reactive N footprint, whereas P loss was reduced by 7%. Similar to the BMP ‘no till with injection’, the lower reduction potential for the 1500-cow farm results from an increase in P run-off losses at this farm which largely off-sets the decrease in sediment-bound P losses. Adoption of no till farming practices increases the net return of the farm by approximately 3%. Similar to the BMP ‘no till with injection’, this increase in profit resulted from a reduced requirement for N fertilizer.

### 3.4.4. Incorporated same day

The BMP ‘incorporated the same day’ reduced the reactive N footprint by approximately 6%, primarily through a substantial reduction (~18%) in NH3-N emission following land application of manure. This NH3-N reduction potential is slightly lower than the predicted reduction potential for manure injection, and broadly consistent with, although lower than, the reduction potentials determined in field studies (range: 50–100%; Maguire et al., 2011; Dell et al., 2012). Field experiments often incorporate manure within minutes of spreading, thus minimizing NH3-N volatilization. In IFSM simulations, manure was left exposed on the soil surface for a few hours before incorporation, which resulted in a lower NH3-N mitigation potential. A small delay in incorporation, as implemented in IFSM is, however, more consistent with commercial farming practice. Similar to manure injection, the reduction potential of manure incorporation was off-set by a predicted increase in N leaching (~10%).

The BMP ‘incorporated same day’ was simulated to have a modest, positive effect (~2% increase) on the net return of both farms. Again, this increase in net return resulted from a decreased requirement in N fertilizer application to corn land, which reduced the costs and increased the farm profit.

### 3.4.5. Summer application

Summer application was simulated to have a minimal effect on the reactive N footprint (~2% decrease) and on the P loss (~2% decrease). For the large farm, NH3 emissions following land application of manure were predicted to decrease (7% reduction), which is consistent with expectations (Rotz, 2004). This decrease was, however, partly off-set by an increase in NH3 emissions from manure storage, which was caused by a larger surface area of the manure storage basin and a longer storage time (Rotz, 2004; Montes et al., 2013). For the 150-cow farm, a larger storage was not needed and with a relatively empty storage during the hot summer months, less emission occurred. The benefits on NH3 emissions from both storage and land application were, however, predicted to be small.

The BMP ‘summer application’ had a modest positive effect on the net return of the 1500-cow farm (~3% increase) and a negligible impact on the net return of the 150-cow farm.

### 3.4.6. Summary

Field management BMPs had a modest effect on reducing the C footprint per unit of milk (0–3% reduction). However, field BMPs can substantially reduce the reactive N footprint (0–19% reduction) and on-farm P losses (1–47% reduction) and are mostly (except cover crops) cost-effective.

### 3.5. Whole-farm mitigation strategy

Whole-farm mitigation strategies were developed based on the most promising individual feed and manure BMPs in terms of C footprint mitigation potential, and the most promising field BMPs in terms of nutrient loss mitigation potential (Table 5).

For both farms, the whole-farm mitigation strategy was predicted to reduce the C footprint, the reactive N footprint and total P losses, while simultaneously increasing the profits of the farm (Figs. 2, 3). For the 1500 cow farm, the whole-farm mitigation strategy reduced the C footprint by 36%, the reactive N footprint by 41%, and the total P loss by 52% (Fig. 2A-C). The annual average milk production and the net return were predicted to increase by 10% and 29%, respectively (Figs. 1, 2D). For the 150-cow farm, the whole-farm mitigation strategy reduced the C footprint by 46%, the reactive N footprint by 42% and total P loss by 40%. Note that the predicted P loss for the 150-cow farm remains higher than the predicted P loss for the 1500-cow farm even after implementation of the whole-farm strategies (Table 3, Table 4). Similar to the baseline scenarios, this discrepancy partly results from the higher manure P application rate on the 150-cow farm in comparison to the 1500-cow farm (27.6 vs. 21.2 kg/ha) and to differences in climate and soil characteristics between the farm locations. The annual average milk production and the net return were predicted to increase by 12% and 33%, respectively (Figs. 1, 3D).

Such C footprint mitigation potentials have been shown in previous studies for other dairy production systems in different locations. For example, Del Prado et al. (2010) predicted that a typical, pasture-based dairy farm in the UK could reduce GHG emissions per liter of milk produced by up to 45% by combining up to 8 best mitigation practices. Similarly, Beukes et al. (2011) predicted a 30% reduction potential (from 0.12 to 0.08 g CO2-eq. / kg FPCM) for a typical pasture-based dairy farm in New Zealand by combining multiple individual mitigation strategies. This supports that C footprint mitigation potentials around 40% are reasonable.

To further contextualize IFSM predictions, we compared IFSM

### Table 5

Whole farm mitigation strategies for the 1500-cow and the 150-cow farm.

<table>
<thead>
<tr>
<th>Farm component</th>
<th>Whole-farm mitigation strategy</th>
<th>1500 cow-farm</th>
<th>150 cow-farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>50% forage rations, high NDF, high feed efficiency, reduced protein</td>
<td>50% forage rations, high NDF, high feed efficiency, reduced protein</td>
<td>Covered manure storage with flare, free-stall barn for heifers</td>
</tr>
<tr>
<td>Manure</td>
<td>Anaerobic digester + solids separation</td>
<td>Covered manure storage with flare, free-stall barn for heifers</td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>Cover crop, no-till system with subsurface injection of manure, summer application of manure</td>
<td>No-till system with subsurface injection of manure, summer application of manure</td>
<td></td>
</tr>
</tbody>
</table>
predictions of GHG emissions and nutrient losses with predictions of other process-based models for the baseline scenarios and the whole-farm mitigation strategies (see SI Section 1). Overall, IFSM predictions of milk production and GHG and reactive N mitigation potential were corroborated by the three other process-based models (CNCPS, Manure-DNDC and EPIC). For P loss, we found substantial differences between IFSM and EPIC predictions. IFSM and EPIC predictions distinctly differed both in terms of pathway-specific P losses as well as in terms of predicted changes in the total field P loss upon implementation of field BMPs. For the 1500-cow farm, IFSM predicted a 50% reduction in the total P loss per unit milk, due to reduced runoff losses of sediment-bound P with cover crop inclusion, a reduction in run-off loss of soluble P due to manure injection, and very little loss through leaching. Although EPIC also predicted a reduction in P losses through a reduction in run-off losses of sediment-bound and soluble P, EPIC predicted a substantial increase in P leaching losses per unit milk, which resulted in a 9% increase in the total P loss upon implementation of field BMPs. The predicted increase in P leaching losses partly resulted from a predicted reduction in corn grain yield by EPIC. In the whole-farm mitigation strategy a lower amount of N is applied, which in EPIC simulations resulted in N stress for corn, thus reducing corn grain yield and plant P uptake. For the 150-cow farm, both models predicted a reduction in P losses upon field BMP implementation, albeit with distinct reduction potentials: IFSM predicted a 40% reduction in total P loss, whereas EPIC predicted a 2% reduction in total P loss. This comparison indicates that further research is needed to evaluate model predictions of all relevant P loss pathways under different management practices.

3.6. Limitations, implications and recommendations

Our results show that implementation of the whole-farm mitigation strategies can substantially reduce the environmental impact of dairy farms in the Great Lakes region, without jeopardizing milk production and farm profitability. It should be emphasized here that we express and compare environmental impacts on a per kg milk basis. This allows for a fair comparison between different farm sizes (here: 1500-cows and 150-cows) and different BMPs, and fits within the context of sustainable dairy production, where improving food production while reducing the environmental impact is key. Although our whole farm mitigation scenarios also reduce the absolute environmental impact of both farms, this is not necessarily the case for individual BMPs that focus on increasing milk production. For example, for the BMP ‘high NDF digestibility’, we predicted that the absolute environmental impact for all impact indicators (C footprint, reactive N footprint, P loss) increased in comparison to the baseline scenario. In this case, the overall environmental impact in a dairy producing region or country can only be reduced when the number of dairy production systems is reduced.

In our approach, we use C footprint, reactive N footprint and P loss as indicators of the potential environmental impact. While C footprint is a good indicator of the global warming potential and P loss is likely a good indicator for the eutrophication potential, reactive N footprint is not necessarily a good indicator for all potential impacts associated with reactive N losses. This is because distinct reactive N losses can contribute to distinct environmental impacts (e.g. NH₃-N contributes to air pollution and N leaching contributes to surface water eutrophication), which can have distinct local impacts and importance. Not explicitly considering the distinct environmental impacts associated with reactive N losses may result in trade-offs. For example, for the 150-cow farm, we predicted a substantial overall reduction in reactive N losses in comparison to the baseline by implementation of the whole-farm mitigation strategy. This reduction was achieved by a substantial decrease in NH₃-N emissions. However, the implementation of the whole-farm mitigation strategy was predicted to increase N leaching losses on the 150-cow farm. While the overall reactive N footprint is reduced, there may be a trade-off between a reduction in air pollution and an increase in eutrophication, which can be of local importance. For the reactive N footprint, a better indication of the potential environmental impact may be obtained by using life cycle impact assessment indicators that are commonly used in life cycle assessment studies (e.g. (Huijbregts et al., 2017)).

We used the IFSM predicted net return as a metric for farm profitability (see Section 2.4). While the net return is a good metric to compare production systems or BMP scenarios in terms of potential, long-term profitability, it is not necessarily a good representation of the future profit of a specific production system as the impacts of income taxes and other government payments and future regulations and policy that may affect the profitability of the business are not included. These factors are difficult to predict and were therefore not included in this study.

Finally, we predicted that the whole-farm mitigation scenarios will increase milk production and farm profits, which are two important factors in BMP adoption by dairy farmers. Yet the likelihood that dairy farmers will adopt the proposed whole-farm mitigation strategies depends on other factors as well. In a meta-analysis of the US BMP adoption literature, Baumgart-Getz et al. (2012) found that the most important factors influencing BMP adoption were the access and quality of information, financial capacity and being connected to agency or local networks of farmers or watershed groups. Preliminary results from a 2017 ‘BMP adoption’ survey conducted on dairy farmers mostly from Wisconsin show that a lack of equipment, insufficient proof of benefit and costs are the leading barriers to adoption of the whole-farm mitigation BMPs “no-till with manure injection”, “low forage rations”, and “sealed manure with biogas flaring”, respectively (Genskow et al., 2018 in prep.). Yet, this ‘BMP adoption’ study also showed that most farmers are open to changes to their operations if specific constraints are addressed (Genskow et al., 2018 in prep.), providing optimism for the future.

4. Conclusion

Implementation of Beneficial Management Practices (BMPs) can mitigate GHG emissions and nutrient losses and reduce the environmental impact of dairy production, but comprehensive, whole-farm studies that evaluate the efficacy of multiple BMPs to reduce multiple environmental impacts and that include an assessment of productivity and farm profitability, are scarce. We performed a systematic evaluation of the C footprint mitigation potential of multiple (10+) farm-component specific BMPs for two representative model dairy farms, a 1500-cow farm in NY and a 150-cow farm in WI, in the US Great Lakes region. In addition to the C footprint, we assessed the effect of BMP implementation on the reactive N footprint, total P losses, as well as milk production and farm profitability. We show that reductions in C footprint per unit of milk are greatest with manure management investments (4–20% reduction) followed by dietary manipulations (0–12% reduction). Field management BMPs had a modest effect on reducing the C footprint per unit of milk (0–3% reduction), but showed substantial potential to reduce the reactive N footprint (0–19% reduction) and P losses (1–47% reduction) and to negate identified trade-offs in total P losses associated with feed and manure BMPs. Our analysis emphasizes the need to assess BMPs in a whole-farm context and not in isolation, as well as the necessity to assess farm profitability in conjunction with the environmental impact assessment. We contextualized IFSM predictions for the whole-farm mitigation strategy by comparing selected predictions to those of three other process-based models (CNCPS, Manure-DNDC and EPIC). While we did observe differences in model predictions for individual flows, particularly for the field, the models generally predicted similar overall mitigation potentials, except for P losses. Overall, we show that an integrated set of individual BMPs can substantially reduce the C footprint, the reactive N footprint and total P losses, while increasing milk production and the net return or profit potential. Further research will focus on assessing the performance of several BMPs under projected future climate change.
Acknowledgements

This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2013-68002-20525. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture. The authors wish to thank Carolyn Betz for her support. We thank the anonymous reviewers for providing valuable comments and suggestions that helped to improve this publication.

Conflicts of interest

None

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.07.005.

References


