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Estimating and comparing cropland nitrogen need with dairy farm nutrient recovery: a case study in Whatcom County, WA

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Abstract

In agricultural regions, like Whatcom County, Washington, crop and dairy production co-exist, but increased agricultural specialization and intensification have divorced what was, historically, an integrated approach to production. This agricultural segregation contributes to farm, regional and watershed-scale nutrient imbalances, and several different management approaches have been devised to improve, correct and close these nutrient cycling disparities. In high-density production regions, utilizing locally produced bio-based fertilizers may provide one avenue toward closing regional nutrient loops. Technologies such as dairy-operated nutrient recovery systems may help improve the flow of nutrients between dairy and cropping systems by extracting nutrients from raw manure and producing materials that are more easily used on farms than raw manure. To evaluate the potential impact of a nutrient recovery system and its related product, we estimated nitrogen balances between cropland use and manure production within Whatcom County, Washington and examined a theoretical scenario in which a specific nutrient recovery product was utilized across the region. We considered one economic barrier, transportation cost, and calculated a hypothetical comparison for transporting nitrogen in two forms, a downstream nutrient recovery product and raw manure. The scenarios presented here demonstrate a potential gap between regional nutrient supply and demand, illustrate the tradeoffs with a technological approach, and make clear that both technological tools and practical management strategies are needed to address the challenges of redistributing nutrients in high-density production areas.

Introduction

With ongoing increases in total dairy cow numbers, herd productivity and concentration over the last half-century, the dairy industry is managing increasing quantities of manure (USDA ERS, 2007; USDA NASS, 2019a, 2019b). Handling, storage and application of these manures and the associated nutrients to soils have, in some areas, contributed to air and water quality impairment (US EPA, 2012; Harter *et al.*, 2017; Ator *et al.*, 2019). The distribution of these nutrients to adjacent crop/horticultural farms, where nitrogen (N) and other nutrients are needed, has been limited due to costs of transport, variable nutrient content and availability, problematic nutrient balance and food safety concerns (Ribaudo *et al.*, 2003; USDA ERS, 2009, 2011; US FDA, 2015). To recouple nutrient cycling between crop and livestock systems, exchanges between specialized livestock and crop farms on a regional level, may be useful (Ryschawy *et al.*, 2017), as these regional exchanges can help overcome practical limitations to farm-level integration (Martin *et al.*, 2016).

Nitrogen is the limiting nutrient in many cropping systems and can reduce water quality if not managed appropriately. Elevated nitrate levels in groundwater are a concern in many agricultural areas, including Whatcom County, Washington (Almasri and Kaluarachchi, 2004). Globally, the influx of N from synthetic fertilizers, produced using the energy-intensive Haber–Bosch process, is at a level that matches naturally occurring N fixation (Galloway *et al.*, 2004). Current anthropogenic perturbation of N cycling represents a high risk of destabilizing the earth's system at a planetary scale (Steffen *et al.*, 2015). One way to reduce excess nutrient loading in the environment is to recycle livestock manure into agroecosystems as a substitute for synthetic fertilizers. When manure is used as a fertilizer substitute, soil physical properties are improved (Naresh *et al.*, 2019), environmentally reactive N is reduced, and soil organic carbon sequestration is improved which effectively improves the coupling in C and N cycling (Xia *et al.*, 2017). However, without accurate accounting for crop nutrient removal and careful attention to soil macro- and micro-nutrient levels, overapplication of manure can result in environmental degradation.

Given the costs of hauling and land-applying manure, dairies and other confined animal feeding operations with liquid manure systems have long used first-generation nutrient recovery systems such as screens and settling basins to recover large solids and/or fibers.

Composting of solids is also used in some cases. Research into newer and more advanced nutrient recovery technologies, such as dissolved air flotation (DAF), is fairly limited (Möller and Müller, 2012; Porterfield *et al*., 2020). Even so, this type of emerging technology may provide a means to reduce manure transportation costs, improve consistency and availability of nutrients relative to raw manure and help producers meet regulatory requirements relating to nutrient management (Yorgey *et al*., 2014; Holly *et al*., 2018). Several technologies are now either in early commercial deployment, being demonstrated at the pilot scale, or still in development. Some technologies complement anaerobic digestion, some are designed to treat non-digested manure and others are flexible. Approaches vary in terms of capital and operating costs, products (and therefore revenue potential to offset costs) and remaining wastewaters (which affects costs of proper disposal) (Drosg *et al*., 2015; Romero-Güiza *et al*., 2016; Frear *et al*., 2018).

To evaluate two advanced nutrient-recovery technologies (DAF and ammonia stripping), a project funded by a Natural Resources Conservation Service (NRCS) Conservation Innovation Grant (CIG) has been underway in Whatcom County, Washington, since 2015, which aims to understand: (1) horticultural impacts, (2) nutrient loss, (3) food safety concerns (Sheng *et al*., 2019; Shen *et al*., 2020) and (4) transportation costs when these products are used in blueberry and raspberry. Bio-based fertilizer products, in this case fine solids separated from dairy manure using the DAF process, also called DAF solids, have a greater nutrient concentration and lower water content [4.5% N, 1.7% P, 0.8% K, 76% moisture (Frear, personal communication)] than raw manure, thus making transport more economical while providing a potential source of nutrients to crops. The DAF process is one of the processes in a category called chemical flocculation/separation that, as of 2019, was being used at 22 facilities in the U.S. for nutrient recovery in dairy manure (Mark Stoermann, Newtrient, personal communication). The DAF process is currently being used on one dairy in Whatcom County and has the potential to facilitate the movement of nutrients from dairies to cropland in a way that improves watershed nutrient balance, soil quality and crop/horticultural production.

The hypothetical scenario explores in this study aims to better understand how nutrient recovery technology could affect the ability to use nutrients from dairies in nearby croplands, using Whatcom County as a case study. We focused on N, specifically, because it is the limiting nutrient in many cropping systems, is the nutrient of greatest concentration in DAF solids and is important for the adoption of DAF solids as an alternative to synthetic fertilizer. We acknowledge that N-based manure management strategies, as opposed to those based upon crop phosphorus (P) needs, can lead to excessive soil test *P* values (Toth *et al*., 2006), which may result in environmental degradation. This scenario, however, considers the effect that a specific nutrient recovery technology, DAF, could have on N nutrient balance and the cost of transporting N to nearby croplands as a means toward understanding the potential and practical challenges associated with nutrient redistribution including the management and environmental concerns that result from the incorporation of additional soil macro- and micronutrients.

In Whatcom County, Washington, there were 96 dairies in 2018 (WSDA, 2018b), with an estimated 45,546 dairy cows (USDA NASS, 2017), as well as 35,810 hectares of cropland (WSDA, 2018a); to estimate N flows in this discrete area, we calculated an N balance based upon total N. We recognize that the focus on total N does not address all of the complexities of N cycling and that the chemical composition of the dairy manure (Mohanty *et al*., 2011) and the biological, chemical and physical properties of the soil determine the rate at which dairy manure N is mineralized (Watts *et al*., 2007, 2010; Fortuna *et al*., 2012). Past studies have considered both N and P budgets by comparing crop nutrient need and nutrients from manure in a discrete geographic area. Most notably, Lander *et al*. (1998), updated as Kellogg *et al*. (2000), calculated N and P balances for each county in the U.S., including Whatcom County, Washington, using data from the Agricultural Census for 1982–1997. In contrast to this approach, we focused solely on nitrogen and combined 1 year's data collected by the Washington State Department of Agriculture (WSDA) with regional nutrient recommendations to illustrate the impacts given a hypothetical scenario of technological adoption.

In this theoretical descriptive analysis, we aim to answer the following questions:

(1) Within Whatcom County, how does the total N available from dairy manure compare to N demand from all cropland, both in terms of total amounts and spatial distribution?
(2) How does concentrating nutrients through the DAF process affect the cost of transporting manure N?

Materials and methods

Data retrieval

Map data were accessed and downloaded from the Washington Geospatial Open Data Portal (http://geo.wa.gov/) and ArcGIS Online (https://www.arcgis.com/index.html). Feature layers displaying Washington State counties and agricultural land use (2018) are courtesy of Washington State Departments of Labor and Industries and Agriculture, respectively (WSDAL&I, 2016). Polygons representing Whatcom County, along with agricultural land use in the county, were clipped and selected for visualization. Dairies within Whatcom County were identified using the Washington Dairies 2018 data layer, also provided by WSDA, which includes detailed information on each facility (e.g., size of dairy herd) used in subsequent calculations. We chose to use only the most recently available data, as our study represents a snapshot in time. Crop data from WSDA showed that between 2009 and 2018, crop area in Whatcom County increased by approximately 20%, with most of this increase due to changes in acres of blueberries, field corn, grass hay, pasture and potato (Perry Beale, personal communication). Despite these changes, the general makeup of crop area in terms of crop groups has remained relatively stable. According to data from the USDA NASS Census of Agriculture data, dairy production in Whatcom County followed the national trend of consolidation, with the number of dairies in Whatcom County declining from 151 to 94 between 2007 and 2017, while the total number of milk cows remained relatively stable during the same time period (48,866–45,546) (USDA NASS, 2007, 2017).

Map estimates

Cropland type and area

The 2018 WSDA agricultural land use data layer was used to illustrate Whatcom county crop type and area. We chose to group crop data based upon the most detailed information available

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for a crop type, except when acreage for a specific crop was low or when nutrient recommendations were unavailable. For example, commercial tree includes three different species (e.g., *Pseudotsuga menziesii*, *Abies procera* and *Populus spp*.) and turfgrass includes golf courses, sod farms and driving ranges; additional groupings are listed in Supplementary Table 1.

Dairies and dairy manure nutrient estimations

Using ESRI's ArcMap 10.6.1 and for illustrative purposes, Whatcom County dairies that were closer than 0.8 km (5 miles) to each other were selected, grouped and represented by a new point feature which was centered geographically between the individual dairies. All attribute tables and characteristics associated with the individual dairies were joined to the newly created point feature and used to assess quantities like total animals, manure, N and DAF N.

For a given dairy, data from WSDA provide ranges for each animal classification (i.e., current calves, dry, heifers and milking) (WSDA, 2018b). Therefore, to estimate the number of animals for an individual dairy, a median was calculated from each animal classification range, summed and used as the estimate for the total number of cows per dairy. From this value and for each dairy, annual manure production was figured as the product of daily manure excretion [estimated for each animal category from Nennich *et al.* (2005)] times 365 days. Additionally, excretion chemical characteristics from Nennich *et al.* (2005) were used to approximate the potential nitrogen content of raw manure which includes both feces and urine. By dividing the weight of total N by the weight of manure, percent nitrogen was figured for each of four animal classifications; from this value, a mean was calculated (0.0055 kg N kg manure^{-1}, or 0.55% N) and used as the multiplier (i.e., % N × total manure) in estimates of total N.

Assuming no in-line nutrient recovery, the regional production of raw dairy manure and potentially available total N were calculated from the dairy, dairy manure and N estimates described above. Because some manure N is volatilized during the manure handling process, the quantity of N in manure as applied to cropland is not 100% of the original manure N. To estimate the potential amount of total N supplied by raw manure under various storage/handling conditions, total N was calculated as the remaining N following a 20 and 50% N loss representing values in the literature for under-floor liquid and open lot storage, respectively (Sutton *et al.*, 2001). This range contains the 30% N loss estimated by USDA NRCS (1998) after storage of cattle manure in an unseparated slurry in a waste storage pond. Thus, the N remaining in raw manure was calculated as a range representing 20–50% loss of N during storage.

Cropland and DAF N calculations

To approximate annual N needs for Whatcom county crops, we multiplied the total area of each crop type by a crop-specific annual N application rate. When available, local nutrient recommendations were used for crop N needs, otherwise nutrient values from other regions were used as substitute values (Supplementary Table 1). Because many crop nutrient recommendations vary in range, the median value for a crop range was selected to represent the N needs. To illustrate the variability in N need, total N needs (for each polygon) were shaded from light to dark based upon total N needs for each field (i.e., increasing color intensity indicates increasing N need). Not accounted for in this estimate are several factors (e.g., soil nutrient status, previous applications of manure, soil organic matter levels) which also play a role in nutrient availability.

Following the use of DAF technology, 28.8% of total N is recovered as DAF from raw manure and parlor water (Craig Frear, personal communication). We multiplied this figure by the total amount of manure produced in Whatcom County to estimate the amount of total N that could be recovered if DAF technology was adopted by all dairy farms in Whatcom County. In our calculations, we assume that the DAF process is implemented following a primary solids separation step (e.g., screening) for all manure generated from a dairy.

Transportation costs and comparison

Transportation costs were calculated using \$0.08 ton^{-1} km^{-1} (\$0.12 ton^{-1} mile^{-1}) (Adhikari *et al.*, 2005; Ghafoori *et al.*, 2007). One dairy was selected as a representative point of origin to assess transportation costs between a DAF product (DAF solids) and raw manure. A distance range of 13–18 km was chosen to illustrate the difference in transportation cost between raw manure and DAF solids. Using the percent *N* values for DAF solids and raw manure as divisors, 4.5 and 0.56% respectively, the amount of material for each amendment was calculated, and then used in the transportation cost equation to figure the dollar amounts for each at both distances (e.g., 13 and 18 km). To equalize the values on a cost per unit N basis, we then transformed the distance cost into a per kg *N* valuation. Distances in both scenarios were estimated in ArcMap by measuring along existing road networks.

Results

Cropland type and area

The distribution of crops grown within Whatcom County, Washington and the total area for each is shown in Figure 1. Twenty-one different crop types were identified where total cropland area summed to 35,810 ha (Fig. 2) and ranged from 0.8 to 12,449 ha for herbs and hay, respectively (Fig. 1). In 2018, fields planted to hay and corn accounted for more than half (54.4%) of total acreage while cane- and blueberries, the next largest categories, occupied 15.6% of acreage with the remaining 30% of cropland planted to 17 other crop types (e.g., pasture, barley) (Fig. 1).

Dairies and dairy manure nutrient estimations

Ninety-six dairies were grouped into 38 different features whose location is evenly distributed throughout the county (Fig. 2). The number of dairies in a feature ranged from one to seven, but 60.5% of features represent less than, or equal to, two dairy locations. Features depicting between three and four, and greater than five dairies represent 29 and 10% of all features, respectively (data not shown).

Annual production of raw manure from Whatcom county dairies is estimated at 1.36 million mg (Fig. 2). Of the 7257 mg of total N contained in this manure, an estimated 3810–6708 mg N is available after handling and storage N loss estimations (20–50%).

Cropland and DAF N

Whatcom county cropland N needs varied considerably (Fig. 3) and was dependent upon the crop type (i.e., N need) and its

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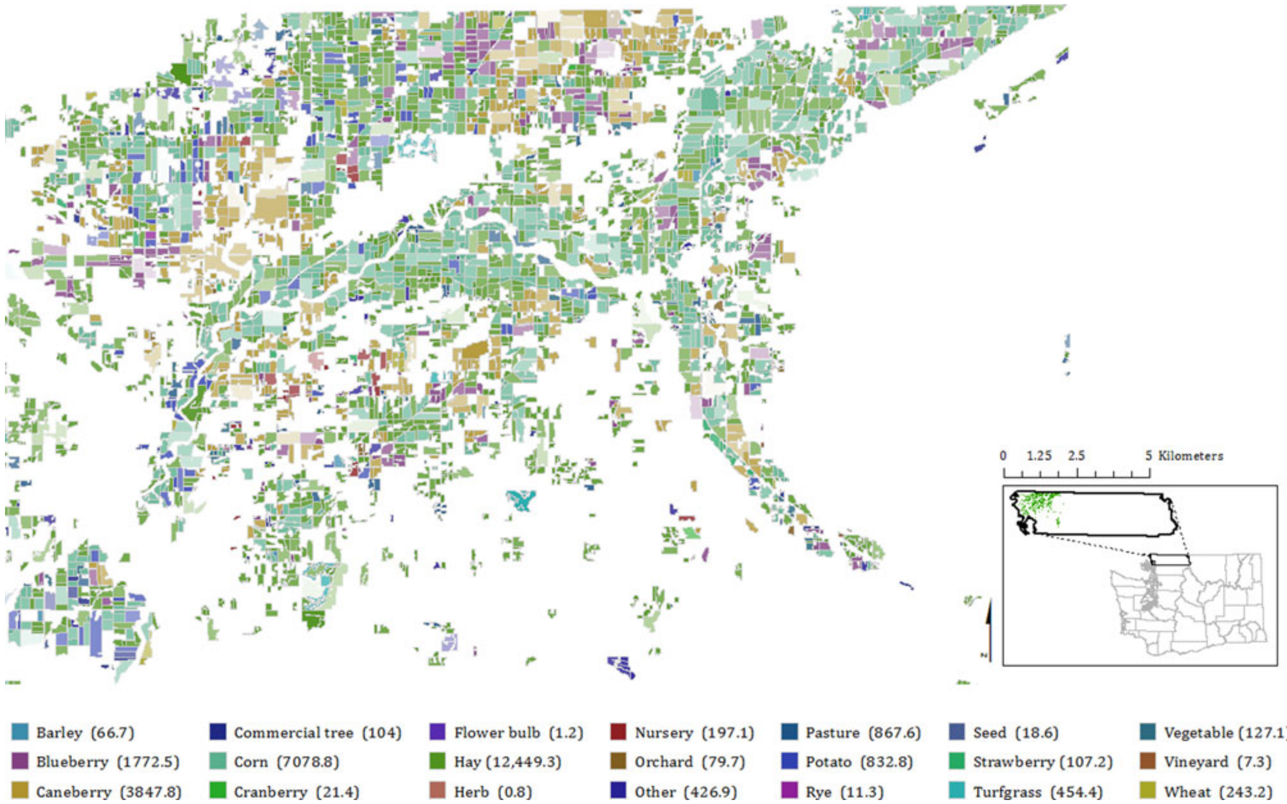

Fig. 1. Crops and area (ha) in Whatcom County, WA where each polygon represents crop field borders and is colored according to crop type. The intensity of the color (i.e., from light to dark) indicates increasing acreage for that crop.

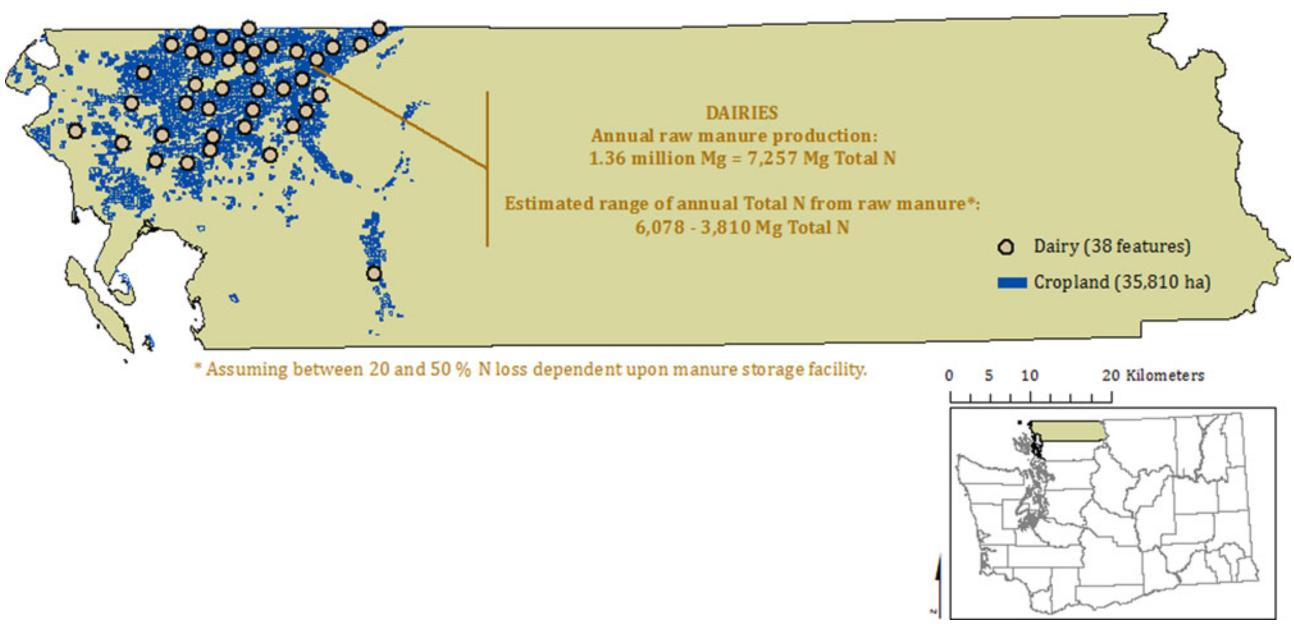

Fig. 2. Dairies (represented as grouped features), total cropland and the annual manure production for Whatcom County, Washington, including total N and the range of available total N following 20 and 50% loss estimates.

total acreage. Estimated annual cropland N needs ranged from 18 to 13,556 kg N for polygons shown in Figure 3. Corn (38.9%), hay (20.7%), caneberry (11%), blueberry (7.9%) and potato (6.3%) accounted for 84.8% of total N need while the remaining 15.2% was distributed between 16 other crop types. Annual cropland N needs for the county summed to 3155.16 mg (Fig. 3). Because some N is lost through denitrification and volatilization after manure application, manure N application rates must be adjusted upward to account for these expected losses. Regional values for N loss for soil conditions in the area and typical

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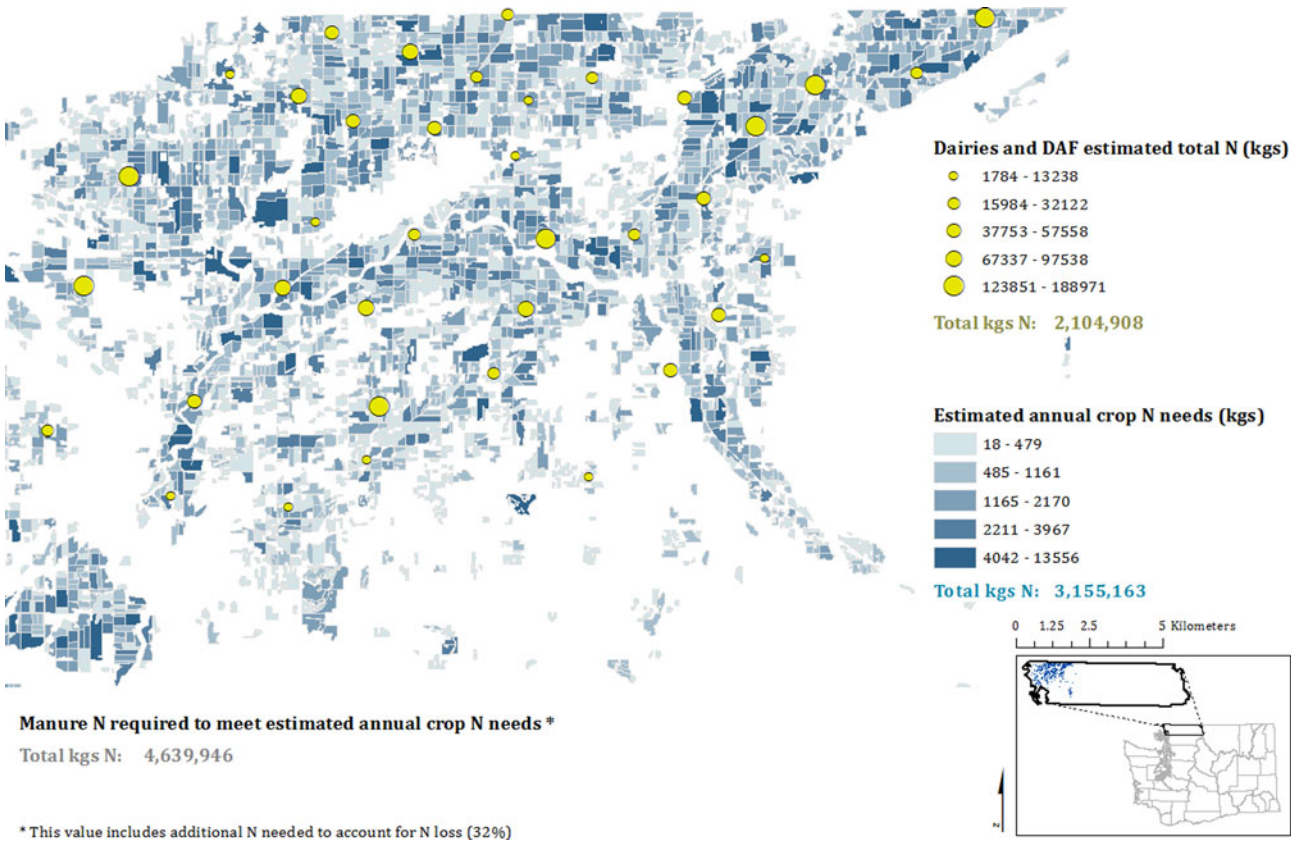

Fig. 3. Estimated annual crop N needs and dairy features illustrating potential N from dairy manure following DAF process, including totals for each. Included is the estimated amount of manure N required to meet annual cropland N needs.

practices for manure application (NRCS, 2006) were applied to the total N to estimate that 68% of manure N would remain in the soil after application. Thus, 4639.9 mg of manure N would need to be applied to meet the cropland N needs (Fig. 3).

As expected, for each of 38 features, total DAF N reflected the total amount of dairy manure available for concentration (Fig. 3). Countywide, DAF total N ranged from 1784 to 188,971 kg N, and 28.7, 38.9 and 32.4% of DAF total N was derived from features representing less than or equal to two, between three and four, and greater than five dairies, respectively. Potential annual production of total N following DAF for all of Whatcom County totaled 2,104,908 kg N (Fig. 3).

Transportation cost and comparison

It costs an estimated \$0.015 to transport 1 kg of manure N 1 km; in comparison, it costs \$0.002 to transport 1 kg of DAF solids N 1 km based on similar assumptions, a sevenfold reduction in cost (Fig. 4). For DAF, transportation costs at a distance range of 13–18 km were estimated at \$0.024 and \$0.035 kg^{-1} N, respectively, while raw manure, for the same distance range, was estimated to cost \$0.192 and \$0.265 kg^{-1} N.

Discussion

In Whatcom County, Washington, the availability of N (in the form of manure) nearly meets or slightly exceeds demand (cropland) (Figs 2 and 3). Based on the calculations described above, annual total N from manure, countywide, ranges from 3810 to 6078 mg (Fig. 2), while manure N required to meet annual cropland N is estimated at 4639.9 mg (Fig. 3). Thus, in Whatcom County, total N availability from manure is between 82 and 131% of cropland N needs. This contradicts the estimates of Kellogg *et al.* (2000), in which it was estimated that recoverable manure N from confined livestock (including beef, swine, dairy and poultry) could supply only 40% of crop N needs in Whatcom County. This discrepancy likely reflects the different methodologies used to estimate manure N amounts (including N losses during manure storage) and cropland N needs. For example, in our study, manure N required to meet cropland N needs were estimated at around 80% of Kellogg *et al.*'s estimate, in part because we assumed a 20–50% loss, which is supported by local technical resources (NRCS, 2006), while Kellogg *et al.* assumed a 60% loss of manure N during storage and handling. In addition, we relied on crop acreage data from the WSDA which employs local specialists who combine crop knowledge and fieldwork to evaluate and verify state cropland inventory (i.e., ground truthing), and we made different assumptions regarding crop N demand by calculating N needs from the most recent local nutrient recommendations.

These discrepancies illustrate the difficulty in estimating regional N balances particularly in agro-ecosystems where variability in crop, amendment and soil is common. For example, not all N applied as manure is immediately available to crops, as N in the organic form must undergo abiotic and biotic processes in order to become plant available; for this reason, only a fraction of the organic N is utilized during the first season of application (van Kessel and Reeves, 2002). In addition, other

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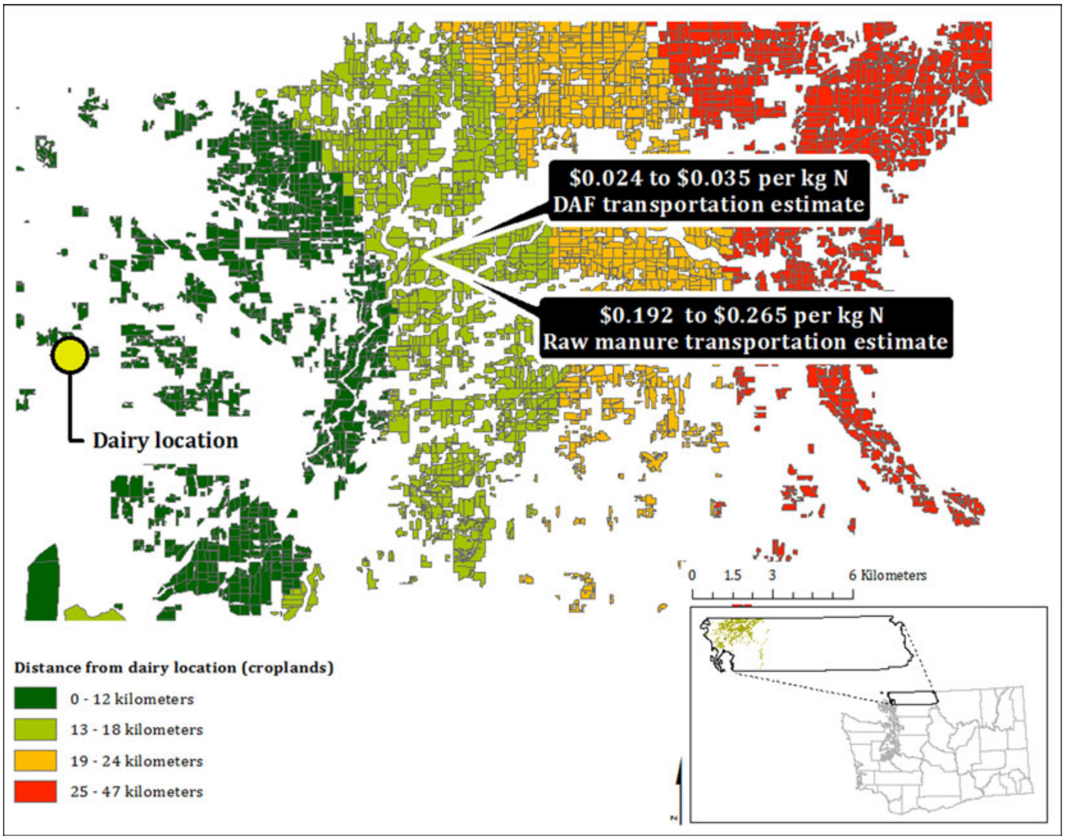

Fig. 4. Transportation scenario illustrating a cost comparison for transporting DAF solids or raw manure 13–18 km (dollars kg^{-1} N) from one dairy location.

N losses (30–50% NH_4-N), like volatilization, are likely to occur during amendment (Thompson and Meisinger, 2002). Further, in a scenario in which repeated annual applications are occurring, the additional N available to a given field in future years would offset the amount that is not available from current-year applications, making balance predictions difficult. Still, theoretical nutrient balances like the one presented here are useful exercises in that, quantitative estimates allow researchers to evaluate potential surpluses or deficits, identify likely problems and consider technological or management strategies that address potential difficulties.

In the scenario where supply exceeds demand, transportation costs are a major limitation in moving manure nutrients beyond the immediate area of the dairy. Since dairy manure has a relatively low nutrient value and a high water content, it is rarely economical for transport to far away fields. A benefit of nutrient recovery processes, such as DAF, is the concentration of manure nutrients into a form that is more economical to transport. Because nutrient recovery products based entirely upon P have yet to prove economically appealing (Mayer *et al.*, 2016), we compared the transportation cost of both DAF solids and raw dairy manure on a per kg of N basis. This difference of over sevenfold could be significant in improving the ability to distribute N from dairy manure to cropland throughout Whatcom County and beyond. In these calculations, we do not account for the fact that dairy manure typically gets diluted by wash water and rainwater before transport to fields. Thus, transport costs for raw manure reflect a best-case scenario, with no additional wash- or rainwater.

If all dairies in the county were to implement nutrient recovery using DAF on all manure produced on these dairies, an estimated 28.8% of manure N could be recovered as DAF solids. Solids from the DAF process cost only 13% as much as raw manure to transport, on a per kg N basis (though this calculation does not consider the production cost for DAF solids). Thus, it should be significantly more economical to transport them over longer distances, leading to better nutrient management outcomes through broader distribution of manure nutrients. However, nutrients can still be lost to the environment from nutrient recovery products or from nutrient-diluted wastewater, especially if these are applied with improper application rates or timing. Thus, nutrient recovery technologies need to be part of a comprehensive strategy to ensure appropriate nutrient application timing and methodology at the farm level, and to address issues of nutrient balance at the watershed level.

Even if transportation barriers are eliminated, the adoption of a nutrient recovery product, and therefore the technology, is dependent upon whether that product meets the practical concerns (i.e., food safety and agronomic performance) of a potential end-user. For example, in 2017, 10,037 hectares (24,803 acres), or 32% of the area classified as 'cropland' in Whatcom County, was treated with manure (NASS, 2017), yet dairy manure is less frequently applied to crops that are grown for human consumption due to food safety concerns and the apprehension that a food safety issue could put a grower out of business and harm the industry. These concerns are exacerbated for crops such as raspberries and blueberries that are generally consumed raw. To address these concerns, a related project looking at the food safety

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of applying raw dairy manure and DAF solids found that dairy manure-derived fertilizers had no impact on food safety in raspberry (Sheng *et al*., 2019) or blueberry (Shen *et al*., 2020) production when application occurred more than 4 months prior to harvest under good agricultural practices. Additionally, another related project looked at the agronomic effects of applying manure and manure-derived fertilizers to raspberries. No difference in growth or fruit yield quantity/quality in raspberries was found between conventional fertilizer, raw dairy manure, composted dairy manure or DAF solids (Benedict, unpublished data).

Because the numbers provided in this report are estimates, there are limitations to this type of analysis. As noted by Sharpley *et al.* (2016) in reference to meta-analyses of P, there can be a disconnect between nutrient analyses conducted at a larger scale and the realities of managing these same nutrients at a farm scale. Further, our calculation assumed N-based nutrient management which does not account for the availability of other nutrients, like P. For a crop area with a history of significant manure application, it may be necessary to apply manure-derived fertilizers based on P needs, rather than the N suggested here. Recent research has shown that by shifting manure management strategies from N-based approaches to P crop removal-based applications, excess soil P accumulation can be significantly reduced, though supplemental N applications may be necessary to maintain yields (Sadeghpour *et al*., 2016, 2017). Additionally, and in this scenario, we have not considered the application of residual liquid from the DAF process, which is high in potassium and water content, and would likely be applied near the dairy, due to transportation costs. Because forage crops grown for dairies would derive more benefit from the balance of nutrients in raw manure than the potassium-rich wastewater from DAF, dairies would likely make a single application of raw manure to their own fields, rather than making two passes to apply both DAF solids and wastewater.

There are, of course, logistical and financial challenges that exist for dairies considering the adoption of nutrient recovery technologies, such as DAF. Current low milk prices create an economic environment in which investment in nutrient recovery technologies is currently highly unlikely despite the increasing regulatory pressures and pressures from consumers. Likewise, crop producers may face hurdles in using these products [e.g., food safety concerns, lack of agronomic information on how they perform in specific cropping systems, concern about whether the nutrient balance meets their crop needs (Hills *et al*., unpublished data)]. Strategies such as incentivizing crop producers may be needed to encourage the adoption of manure and bio-based fertilizers derived from manure as inputs in crop production (Centner, 2004). Despite these uncertainties, the calculations above show the potential—and the substantial remaining challenges—for nutrient recovery to improve nutrient cycling between crop and livestock operations, and thus, improve the sustainability of agroecosystems. The hope of the authors is that this analysis will prompt discussion of ways to better utilize manure nutrients in cropping systems and provide information on how the utilization of nutrient recovery technologies (DAF) can potentially facilitate transportation of nutrients. Continued attention to these challenges will contribute to the development of feasible models that improve the long-term sustainability of the dairy industry, in particular, and agricultural systems, in general.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170520000198.

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