Abstract

With increasing demand for land and food, there is growing interest in sustainable intensification of agricultural production. Here we investigated sustainable intensification of grass and corn production for dairy farms using a system of semi-virtual farmlets that combine replicated field research plots with feed modelling. We improved manure N capture by spreading separated liquid fraction with a low emission sliding shoe applicator on grass, and manure P capture by precision injecting separated sludge into corn. Reducing the number of annual harvests (from 5 to 3) increased grass yield and interseeding Italian ryegrass in early maturing corn increased fall growth of the cover crop, thus helping to protect soil over winter and providing additional high quality herbage in spring. Irrigation improved yield and potentially yield stability of corn and grass, and adding a nitrification inhibitor to reduce N₂O emission may help reduce pollution swapping especially from injected manure. Overall, allocating more land to corn than grass will increase farm productivity but effectiveness of measures to reduce pollution and pollution swapping need to be evaluated. Results show that good practices ensuring vigorous crops are challenging to implement but critical for achieving sustainable intensification. The semi-virtual farmlet system is very helpful for developing and evaluating sustainable production measures for corn and grass.

Introduction

Agriculture is often blamed for environmental harm due to mismanagement of farm nutrients. Excessive nutrients and inadequate handling leads to leakages of nitrogen (N) and phosphorus (P) into the environment with consequences to human and ecosystem health including climate change (Sutton et al 2011). It is important for long term food and environmental security that farms be managed in accordance with both regional and global sustainability goals.

The livestock sectors worldwide have been criticized for reasons that include excessive regional importation of nutrients, imprudent manure application on fields, fugitive emissions from land and structures, all potentially degrading nutrient use efficiency (Leip et al 2015). The inefficiency of converting vegetation into livestock products compounds the inefficiencies inherent in crop production, although the environmental costs are mitigated by amenities associated with animal agriculture such as use of perennials in crop rotations and the upcycling of inedible perennial crops, substandard foods, wastes and by-products. The livestock industry inevitably provides valuable crop nutrients as manures.

The dairy sector is particularly complex owing to exacting feed formulations which must be matched closely to nutritional requirements of each group of cows. Farmers must produce and store high quality home-grown feeds that meet requirements such as energy and rumen-by-pass protein (Bava et al 2014). The high producing dairy farms in British Columbia (BC), Canada and elsewhere often supplement their homegrown feed with...
purchased feedstuffs and additives to optimize feed rations but adding to farm costs and nutrient balance (Lorenz et al. 2019).

Improving farm nutrient balance and efficiency requires that main farm outputs, milk and animals, be increased and farm inputs, feeds, fertilizer and bedding, be reduced by better use of manure and increased crop production. Also, production methods need to minimize farm nutrient losses. Over the past 20 years, the dairy industry across Canada and other regions, through advances in feeding and genetics, has improved milk yield per cow (Bach et al. 2020), hence milk per hectare (ha), and this can be viewed as sustainable intensification. Intensification has also involved a shift from grazing to production of high producing often irrigated crops like corn (Aarts et al. 2000). Sustainable intensification is needed in BC due to a declining agricultural land-base and increasing demands for milk.

Importation of feeds and by-products (Chobtang et al. 2017) or billeting replacements animals transfers pollution away from the farm. The transferred impacts may be justified in terms of minimizing overall impact of milk production but must be carefully considered, especially for nutrient recycling. Clearly sustainable intensification requires understanding dairy systems at multiple levels (Bava et al. 2014, Lorenz et al. 2019). To understand dairy systems and how to improve their function several tools have been used. Dairy systems in the Netherlands have been studied using a working ‘model farm’ employing sustainable measures which were carefully monitored over many years (Aarts et al. 2000). Detailed study of multiple pilot farms over several years under ‘Cows and Opportunity’ program in the Netherlands has helped to identify the most effective practical measures for conserving nutrients (Oenema et al. 2011). Experimental farmlets have been used in New Zealand to assess the impacts of farm intensification relative to commercial farms (Basset-Mens et al. 2009). Dairy systems have also been investigated using dynamic process models (IFSM) and statistical models (HOLOS) reflecting the connection between environment, crops, animals and humans (Little et al. 2017, Veltman et al. 2018).

The current study in the peri-urban region near Vancouver, BC, was designed to explore novel measures for sustainable intensification in the context of whole dairy farms. We developed a method referred to as ‘semi-virtual farmlets’ which combines field trials of replicated farm-like units (Farmlet), consisting of corn and grass, with feed ration software such as Cornell Net Carbohydrate and Protein System (4 AMTS, Agricultural Modeling and Training Systems LLC, Groton, NY). This allows modeling of animal performance based on the field experiments including quality determination of crop samples related to the field trial treatments in order to understand outcomes such as cow intake, feed supplementation, milk production and nutrient excretion. The field study allows consideration of novel management practices, for each crop, intended to facilitate overall feed optimization or, conversely, the cropping possibilities can be assessed in terms of milk production outcomes. It is assumed that the feed ration model is a powerful tool to predict dairy cow performance due to its well established use by the dairy industry. The current manuscript focuses on agronomic results from the field study over two years. Environmental effects and detailed milk production scenarios will be reported subsequently.

The Farmlet systems here are based on high-intensity, fully confined dairy farms located in the moderate, maritime climate of coastal BC. Typical dairy farms in this region grow mainly grass and corn (60 and 40% of land, respectively) and import about 40% of their feed as concentrate, alfalfa hay and straw. The hypothesis of this study is that farm nutrient efficiency can be improved with strategic internal nutrient cycling combined with improved homegrown feed production which together will improve nutrient uptake and reduce farm balances. The study investigates four experimental Farmlets with contrasting corn- and grass-specific practices: Farmlet 1 (Reference farm); Farmlet 2 (Improved nutrient cycling); Farmlet 3 (Improved nutrient cycling plus enhanced cropping practices); Farmlet 4 (Best management, enhanced practices beyond those in Farmlets 2–3).

The objectives of the study are to 1. assess a suite of locally tested practices with widespread applicability intended to improve production and reduce environmental impact of intensively managed grass and corn; 2. determine best management practices and cropland allocations for farm milk production in BC. The current manuscript focuses on the interrelationship between plant productivity, nutritional quality, plant nutrient uptake and nutrient recovery rate on a dairy farm ecosystem subject to alternative management practices. Subsequent manuscripts will describe environmental effects and potential animal performance.

Materials and methods (for details see SI1)

The experiment was carried out over 24 months in 2016 to 2018 on a field previously rotated between corn and grass, located in south coastal British Columbia, Canada (49°25’ N, 121°76’ W), a region with a moderate maritime climate (Table S1 and Figure S1). The field has a flat terrain (slope <2%) with soil (0–15 cm) properties: ~6% organic matter, 1.17 g cm⁻³ bulk density, 129 g kg⁻¹ sand, 195 g kg⁻¹ clay. Nutrient properties, rates and application dates are reported in tables 1, 2 and S1.
The experiment was laid out as a split plot within 4 randomized complete blocks; main plots are perennial tall fescue grass and corn and sub-plots are 4 Farmlets (details in Supplemental Information (available online at stacks.iop.org/ERC/3/075009/mmedia)); Farmlet 1 (F1, Reference farm); liquid dairy manure (slurry) is broadcast on corn and grass, corn also receives commercial N and P fertilizer by injection near the seed at planting to support early growth (called side-banding) and a band of commercial N fertilizer near the crop row at about the 9-leaf stage (V9) (called side-dress); a long season corn hybrid provides maximum yield; an early maturing tall fescue variety is harvested 5x yr⁻¹ for high forage quality including crude protein (CP) and total digestible nutrients (TDN).

Farmlet 2 (F2, Improved nutrient cycling); grass received only the thin liquid supernatant after slurry has settled for several months (low P and DM) applied by banding beneath the crop canopy with tubes (called trailing shoes) that ride independently on the soil surface to minimize gaseous (especially ammonia) emissions; corn received the settled sludge (high DM and P) by precisely injecting within 10 cm of corn row substituting for commercial ‘starter’ fertilizer; urea fertilizer was side-dressed (see above) at 9-leaf stage (V9) according to soil test.

Farmlet 3 (F3, Improved nutrient and cropping management); nutrients managed as F2; a short season high-grain corn hybrid harvested in early Sept. to favour fall growth of cover crop; cover crop (Italian ryegrass) was inter-planted in corn at 6-leaf stage (V6), received separated liquid fraction (see above) in March, harvested in April and cultivated out before replanting corn; perennial grass crop was harvested 3x yr⁻¹ to increase yield.

Farmlet 4 (F4, Best management); Nutrient and crop management as in F3 with summertime irrigation and a nitrification inhibitor added to manure.

All plot samples were field-weighed, dried at 60 °C, reweighed and ground. Plant N concentration was determined using the dry ash method and P was analyzed with a spectrophotometer after a sulphuric acid-selenium-hydrogen peroxide digestion. Above-ground corn N and P uptake were calculated as N or P concentration × above-ground whole plant biomass. Plant nutrient recovery was calculated as N or P uptake/ N or P applied (as manure plus fertilizer). TDN and potential milk production were determined using the yield and nutrient analysis data of silage corn as input for MILK2006 and of grass as input for MILK2016. Inputs for MILK2006 were DM yield, and percent values for; DM, CP, neutral detergent fiber (NDF), \textit{in vitro} NDF digestibility (NDFD), starch, ash and a book value of 3.2% for ether extract. Inputs for MILK2016 were DM yield, and percent values for; CP, NDF, \textit{in vitro} NDFD, ash and a book value of 2.28% for ether extract. CP was calculated as %N × 6.25. NDF was determined using the ANKOM Fiber Analyzer with heat-stable α-amylase and sodium sulfite. \textit{In vitro} 30-h NDF degradability was determined using the filter bag technique. Silage corn samples were further ground using a ball grinder (Mixer Mill MM2000; Retsch, Haan, Germany) for

| Table 1. Attributes of whole dairy slurry and liquid and sludge fractions which were separated by settling used in the Farmlet trial in 2017 and 2018. |
|-----------------------------------------------|------------------|-----------|-----------|
| Manure type                              | Parameters        | Unit | 2017   | 2018   | Mean   |
| Whole Slurry                             | Dry matter        | %    | 4.9    | 4.5    | 4.7    |
|                                           | Total ammoniacal N | g kg⁻¹ | 1.5    | 1.2    | 1.3    |
|                                           | Total N           | g kg⁻¹ | 2.3    | 2.2    | 2.3    |
|                                           | TAN/TN            | g kg⁻¹ | 0.6    | 0.6    | 0.6    |
|                                           | TP                | g kg⁻¹ | 0.4    | 0.3    | 0.4    |
|                                           | TN/P              |        | 6.1    | 6.7    | 7.2    |
|                                           | pH                |        | 7.3    | 7.2    | 7.2    |
| Separated Liquid Fraction                 | Dry matter        | %    | 3.6    | 2.5    | 3.1    |
|                                           | Total ammoniacal N | g kg⁻¹ | 1.1    | 1.0    | 1.0    |
|                                           | Total N           | g kg⁻¹ | 2.0    | 1.7    | 1.8    |
|                                           | TAN/TN            | g kg⁻¹ | 0.6    | 0.6    | 0.6    |
|                                           | TP                | g kg⁻¹ | 0.3    | 0.2    | 0.2    |
|                                           | TN/P              |        | 7.7    | 8.7    | 8.2    |
|                                           | pH                |        | 7.3    | 7.2    | 7.3    |
| Separated Sludge Fraction                 | Dry matter        | %    | 7.9    | 9.1    | 8.5    |
|                                           | Total ammoniacal N | g kg⁻¹ | 1.7    | 1.5    | 1.6    |
|                                           | Total N           | g kg⁻¹ | 3.2    | 2.9    | 3.1    |
|                                           | TAN/TN            | g kg⁻¹ | 0.5    | 0.5    | 0.5    |
|                                           | TP                | g kg⁻¹ | 0.5    | 0.4    | 0.5    |
|                                           | TN/P              |        | 6.5    | 6.7    | 6.6    |
|                                           | pH                |        | 7.0    | 6.8    | 6.9    |
determination of starch by enzymatic hydrolysis of α-linked glucose polymers. Glucose was determined using glucose oxidase-peroxidase.

Crop year for silage corn was set by production, April-April, so that cover crop yields were added to the previous corn yields. Crop year for tall fescue was from March to March based on the date of first manure application. Effects of Farmlet management were analyzed separately for each crop using a linear mixed effects model with four management scenarios (F1 to F4) and crop year (2017–18 and 2018–19) as fixed effects and block as a random effect. Type III ANOVA estimated differences in factor means and separated using Fisher’s protected LSD. When farmlet*year interactions were significant, the least squared means of each factor level were tested across the years. Data were tested for normality using the Shapiro-Wilk test, and when not normal were log-transformed to meet normality assumptions, then retransformed for reporting. All analyses were carried out in R (R Core Team 2017).

Results and discussion

The management measures are different for grass and corn so Farmlets are compared only within crop, but the design allows crops to be compared. Complete Farmlet constructs, comprised of corn and grass plots, were optimized by varying grass:corn land ratios.

F1: Reference farm

The reference farmlet (F1) featured a long-season corn hybrid for maximum yield planted in mid-May and harvested in late September (Table S1), thus limiting favourable growing conditions for a fall cover crop (figure 1, table 3), so none was planted. The grass in F1, widely-used tall fescue, was harvested 5x yr⁻¹ for high nutritional quality (CP and TDN).

Whole slurry was applied to bare corn land and grass by surface broadcasting with no immediate incorporation. Dates of application are shown in table S1. Rates of manure plus fertilizer (TN) used were consistent with local practice at 297 and 565 kg N ha⁻¹ for corn and grass, respectively (table 2). Thus for a farm with typical 60:40 grass:corn ratio, average farm N rate used in F1 is calculated at about 458 kg N ha⁻¹. Based on the local farm stocking density of 2.5 lactating cows ha⁻¹, plus 30% dry cows and 40% replacement heifers, and excretion rates of 179, 83 and 43 kg TN cow⁻¹ yr⁻¹, respectively, the average annual N excretion on commercial

| Table 2. Rates of mineral (synthetic) N and P, total ammoniacal-N (TAN) and total (organic and inorganic) N (TN) and total P (TP) from manure and fertilizer applied to silage corn, winter cover crop, and perennial grass across 4 Farmlets in 2017 and 2018. |
| Management Scenario | Synthetic N<sup>a</sup> | Total ammoniacal N<sup>b</sup> | Total N<sup>c</sup> | Synthetic P<sup>d</sup> | Total P<sup>d</sup> |
|---------------------|-----------------|-----------------|----------|-----------------|-----------------|
|                     | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Silage Corn         |      |      |      |      |      |      |      |      |      |      |
| Farmlet 1           | 75   | 75   | 187  | 202  | 282  | 312  | 40   | 40   | 71   | 75   |
| Farmlet 2           | 55   | 55   | 169  | 170  | 271  | 288  | —    | —    | 34   | 35   |
| Farmlet 3           | 55   | 55   | 173  | 171  | 278  | 289  | —    | —    | 35   | 35   |
| Farmlet 4           | 55   | 55   | 165  | 170  | 264  | 288  | —    | —    | 32   | 35   |
| Winter Cover crop   |      |      |      |      |      |      |      |      |      |      |
| Farmlet 3           | —    | —    | 67   | 70   | 124  | 121  | —    | —    | 15   | 16   |
| Farmlet 4           | —    | —    | 67   | 62   | 124  | 121  | —    | —    | 15   | 15   |
| Perennial grass      |      |      |      |      |      |      |      |      |      |      |
| Farmlet 1           | —    | —    | 345  | 299  | 586  | 543  | —    | —    | 98   | 85   |
| Farmlet 2           | —    | —    | 407  | 310  | 673  | 537  | —    | —    | 96   | 64   |
| Farmlet 3           | —    | —    | 409  | 327  | 694  | 559  | —    | —    | 93   | 67   |
| Farmlet 4           | —    | —    | 404  | 320  | 684  | 564  | —    | —    | 91   | 68   |
| Farmlet with 50/50 area ratio of each crop |      |      |      |      |      |      |      |      |      |      |
| Farmlet 1           | 38   | 38   | 266  | 250  | 434  | 428  | 20   | 20   | 85   | 80   |
| Farmlet 2           | 23   | 23   | 288  | 240  | 489  | 413  | —    | —    | 65   | 50   |
| Farmlet 3           | 23   | 23   | 325  | 284  | 548  | 485  | —    | —    | 72   | 59   |
| Farmlet 4           | 23   | 23   | 318  | 276  | 536  | 487  | —    | —    | 69   | 59   |

<sup>a</sup> Mineral fertilizer were 11-52-0 (20 kg N ha⁻¹ as starter for Farmlet 1) and 46-0-0 (55 kg N ha⁻¹ as side-dress on all Farmlets but was based on soil test at V9 only for Farmlets 2–4)

<sup>b</sup> TAN: total ammonium nitrogen from both mineral fertilizer and manure.

<sup>c</sup> TN: total Kjeldahl organic nitrogen plus mineral fertilizer

<sup>d</sup> TP: total phosphorus from both mineral fertilizer and manure.
farms is about 550 kg N ha$^{-1}$, subject to feeding regimens (Nennich et al 2005). For F1, it is estimated that about 25% of TAN or 15% of TN (based on 60% TAN) was lost by ammonia volatilization from buildings and storages (Sheppard et al 2011), leaving about 468 kg N ha$^{-1}$ to apply across the farm. Actual application of N to corn (297 kg ha$^{-1}$) included 222 and 75 kg ha$^{-1}$ of manure and mineral fertilizer N, respectively, the latter comprised of 20 kg ha$^{-1}$ side-banded at planting as di-ammonium phosphate and 55 kg ha$^{-1}$ side-dressed as urea at V9 (Table S1). No mineral fertilizer was applied on the grass in F1, although this is sometimes done by farmers in mid-summer in the belief that crop injury could result from manure applied during hot weather, though none was observed in this study. Reducing N and P application rates on the farm would require that no mineral fertilizer is purchased and that less N and P are excreted by reducing stocking rates (including off-farm billeting of replacement heifers) or lowering nutrient excretion with more precise rations. There are new opportunities for exporting nutrients as filtered manure solids for use on nearby dairy and horticultural operations as bedding or mulch (Franzluebbers et al 2021).

With reference practices, corn and grass in F1 produced an average annual yield of 20.1 (48.8% grain) and 10.7 t DM ha$^{-1}$, respectively (tables 3–5). Corn yield was higher in 2017 while grass yield greater in 2018, so the two crops dampened annual yield variation, a feature of the crop pairing valued by farmers. Mean N uptake over the two years was 259 and 180 kg ha$^{-1}$ for grass and corn, respectively (tables 6 and 7), representing N recoveries (N uptake/N applied) of 0.60 to 0.46 for corn and grass, respectively. The higher recovery rate for corn was due

Figure 1. Effect of relative land area allocation to grass and corn on dry matter yield, yield of total digestible nutrients (TDN) and expected milk production using the MILK formula for four Farmlets (mean of 2017 and 2018). Data in table S2.
to a higher proportion of inorganic N (65 and 57% for corn and grass, respectively, table 2) and 20%–30% lower grass yields than usual (discussed below). Based on the 60:40 grass:corn land ratio, mean N uptake was 227 kg N ha$^{-1}$ across the farm representing ∼50% N recovery rate and ∼225 kg ha$^{-1}$ of surplus N. Approximately 60% of TAN or 35% of total N was estimated to be lost as NH$_3$ from slurry surface broadcast on bare corn soil or recently cut grass (Søgaard et al 2002). Thus, of 427 kg N ha$^{-1}$ applied as slurry only ∼320 kg ha$^{-1}$ was likely available to the crop with the remaining 95 kg ha$^{-1}$ lost by denitrification, leaching or remaining in the soil, the latter we estimate at 10% of applied N to grass or about 34 kg ha$^{-1}$ farm average based on Bittman et al (2007). We expect little accumulation of soil N in corn fields because N is lost mainly as nitrate through the winter (Verloop et al 2014).

Table 3. Dry matter yield of silage corn and winter cover crop (Italian ryegrass) on the corn land of each of 4 Farmlets in 2 years. Cover crops were only planted in Farmlets 3 and 4.

| Management scenarios | Crop Dry-matter (t DM ha$^{-1}$) | 2017–18 | 2018–19 | Mean |
|----------------------|---------------------------------|---------|---------|------|
| Silage corn whole     |                                 |         |         |      |
| Farmlet 1            | 20.80 a                        | 19.43 b | ab      | 20.12 a |
| Farmlet 2            | 19.99 a                        | 20.53 b | a       | 20.26 a |
| Farmlet 3            | 16.76 b                        | 14.34 c | c       | 15.65 c |
| Farmlet 4            | 17.78 b                        | 17.41 b | b       | 17.60 b |
| Mean                 | 18.84 A                        | 17.98 A | A       | —     |
| LSD$_{0.05}$         | 2.13 2.11                      | 1.24    |         |       |
| Winter cover crop    |                                 |         |         |      |
| Farmlet 3            | 2.63 b                         | 2.67 a  | a       | 2.65 a |
| Farmlet 4            | 2.90 a                         | 2.50 a  | a       | 2.69 a |
| Mean                 | 2.76 A                         | 2.58 A  | A       | —     |
| LSD$_{0.05}$         | 0.16 0.21                      | 0.26    |         |       |
| Silage corn plus Winter cover crop |            |         |         |      |
| Farmlet 1            | 20.80 a                        | 19.43 a | a       | 20.12 a |
| Farmlet 2            | 19.99 a                        | 20.53 a | a       | 20.26 a |
| Farmlet 3            | 19.38 a                        | 17.21 b | b       | 18.30 a |
| Farmlet 4            | 20.67 a                        | 19.91 a | a       | 20.29 a |
| Mean                 | 20.21 A                        | 19.27 A | A       | —     |
| LSD$_{0.05}$         | 2.17 2.10                      | 1.49    |         |       |

* Farmlet values in each column followed by different lower case letters are significantly different by Fisher’s protected least square difference (LSD, P < 0.05).

Table 4. Corn grain yield and harvest index for each of 4 Farmlets in 2 years.

| Management scenarios | Corn grain yield (t DM ha$^{-1}$) | 2017–18 | 2018–19 | Mean |
|----------------------|---------------------------------|---------|---------|------|
|                       |                                 |         |         |      |
| Farmlet 1            | 9.18 a                          | 10.29 a | 9.74 c  | 0.445 b |
| Farmlet 2            | 8.89 a                          | 10.75 a | 9.82    | 0.448 b |
| Farmlet 3            | 8.66 a                          | 7.16 b  | 7.91    | 0.515 a |
| Farmlet 4            | 9.26 a                          | 8.30 b  | 8.78    | 0.523 a |
| Mean                 | 9.00 A                          | 9.13 A  | A       | 0.483 B |
| LSD$_{0.05}$         | 1.09 1.25                       | 1.06    |         | 0.024 0.033 |

* Farmlet values in each column followed by different lower case letters are significantly different by Fisher’s protected least square difference (LSD, P < 0.05).

* Annual mean values in each row followed by different upper case letters are significantly different by Fisher’s protected least square difference (LSD, P < 0.05).

* Significant difference between 2-year means of each farmlet are not shown given farmlet * year interactions are significant.
The average P recovery on the reference farmlet was 33.9 and 27.2 kg ha\(^{-1}\) for corn and grass, respectively (tables 7 and 8). Based on applications of 73 and 92 kg P ha\(^{-1}\) (fertilizer plus manure), annual surplus P was 39.1 and 64.3 kg ha\(^{-1}\) for corn and grass, respectively, or 54.2 kg ha\(^{-1}\) for the whole farm (based on 60% grass of which 16 kg ha\(^{-1}\) is from starter corn fertilizer. Dairy farm soils in the region are currently high in P so surplus inputs must be avoided (Sullivan and Poon 2016).

### F2: Improved nutrient use

F2 employs integrated practices to improve utilization of slurry nutrients by grass and corn. The primary strategy, called dual manure stream (Bittman et al 2013), involves simple separation of dairy slurry into a thin fraction with low dry matter, total N and P concentrations (Bittman et al 2011) and a sludge fraction with higher dry matter, organic N and P concentrations (Bittman et al 2012). Solid liquid separation can be performed by many means but here we partially separated the fractions by allowing the solid particles to passively settle (see SI1). The thin fraction is a good primary N source for grass because of a high N recovery rate, probably due to rapid soil infiltration and low ammonia losses; also its high N:P ratio reduces P loading so it can be applied near agronomic N rates (Bittman et al 2011). The thicker high-P sludge is injected as the sole P source for corn, replacing mineral starter, by precision placement of corn near sludge furrows (see SI1) (Bittman et al 2012).

The liquid fraction was banded on grass 5x annually (one dose for each growth period) using a trailing shoe to reduce ammonia emissions and improve N recovery and application uniformity (Bittman et al 1999, Webb et al 2010). The liquid fraction also favours N recovery compared to whole slurry because its lower content of organic N (Bhandral et al 2009, Bittman et al 2011), but there was little difference in TAN:TN in this study.
indicating the need for better separation technology (table 1). The application rate in F2 averaged 605 kg N ha\(^{-1}\) which was higher than F1 in 2017 but similar in 2018 (table 7). The DM yield was similar for F2 and F1 in 2017 suggesting that other factors were limiting yield, but F2 yield was significantly higher in 2018 (table 5). N recovery ratio and CP content, averaged over years, was significantly higher for F2 reflecting the more effective thin fraction and sliding shoe application method (tables 7 and 9). Although grass P uptake in both F1 and F2 was similar over years, recovery ratio was significantly greater in F2 which had received less P from the liquid fraction in 2018. Overall, P loading on grass in F2 was reduced by 11.5 kg ha\(^{-1}\) yr\(^{-1}\) although the average annual surplus was still 53 kg P ha\(^{-1}\) (35.1 in 2018) which is higher than reported by Bittman et al (2011) and suggests the need to improve farm P balance and P separation efficiency.

### Table 6. Annual total N application on corn and winter cover crop, and annual crop N uptake and ratio of N uptake to applied total N across 4 Farmlets in two years.

| Management Scenario | Total N applied (kg ha\(^{-1}\)) | Crop N uptake (kg ha\(^{-1}\)) | Crop N uptake/N applied (ratio) |
|---------------------|---------------------------------|-------------------------------|---------------------------------|
|                     | 2017–18                         | 2018–19                       | Mean 2017–18                    |
| Corn                |                                 |                               |                                 |
| Farmlet 1           | 282                             | 312                           | 170 b\(^{\ddagger}\) 189 ab 180 bc | 0.603 b 0.605 ab 0.604 b |
| Farmlet 2           | 271                             | 288                           | 181 ab 205 ab 193 ab           | 0.667 ab 0.712 a 0.690 a |
| Farmlet 3           | 278                             | 289                           | 178 ab 163 b 170 c           | 0.641 b 0.563 b 0.602 b |
| Farmlet 4           | 264                             | 288                           | 199 a 200 a 200 a           | 0.754 a 0.695 a 0.724 a |
| Mean                | 182 A 189 A                     |                                | 0.666 B\(^{\ddagger}\) 0.644 A | --- |
| LSD\(_{0.05}\)       | 10                              | 27                            | 9                              | 0.074 0.107 0.060 |
| Cover crop          |                                 |                               |                                 |
| Farmlet 3           | 124                             | 121                           | 61 a 79 a 70 a             | 0.493 b 0.653 a 0.573 a |
| Farmlet 4           | 123                             | 121                           | 65 a 65 a 65 a             | 0.530 a 0.537 a 0.533 a |
| Mean                | 63 B 72 A                       |                                | 0.511 B 0.595 A          | --- |
| LSD\(_{0.05}\)       | 10                              | 27                            | 9                              | 0.026 0.132 0.050 |
| Corn plus Cover crop|                                 |                               |                                 |
| Farmlet 1           | 282                             | 312                           | 170 c 189 b 180 c           | 0.604 b 0.605 b 0.604 c |
| Farmlet 2           | 271                             | 288                           | 181 c 205 b 193 c           | 0.668 b 0.713 a 0.691 ab |
| Farmlet 3           | 401                             | 410                           | 238 b 242 a 240 b          | 0.594 b 0.589 ab 0.591 bc |
| Farmlet 4           | 387                             | 409                           | 264 a 265 a 265 a          | 0.683 a 0.649 a 0.666 a |
| Mean                | 213 A 225 A                     |                                | 0.637 B 0.639 A          | --- |
| LSD\(_{0.05}\)       | 10                              | 27                            | 9                              | 0.061 0.080 0.048 |

\(^{\ddagger}\) Farmlet values in each column followed by different lower case letters are significantly different at P < 0.05.

\(^{\ddagger}\) Annual mean values in each row followed by different upper case letters are significantly different at P < 0.05.

### Table 7. Total annual application of N and P on perennial grass, total grass uptake of N and P, and N and P uptake per N and P application across 4 Farmlets in two years.

| Management Scenario | Total applied | Grass Nutrient Uptake | Grass Nutrient Uptake/Nutrient Applied |
|---------------------|---------------|-----------------------|---------------------------------------|
|                     | 2017 2018     | 2017 2018 Mean        | 2017 2018 Mean ratio                  |
| Annual total N      |               |                       |                                       |
| Farmlet 1           | 586 543       | 229 c 289 b 259 c     | 0.390 b 0.533 b 0.462 c              |
| Farmlet 2           | 673 537       | 255 b 348 a 301 b     | 0.360 b 0.648 a 0.504 b              |
| Farmlet 3           | 694 559       | 271 b 345 a 308 b     | 0.391 b 0.616 a 0.503 b              |
| Farmlet 4           | 684 564       | 303 a 366 a 335 a     | 0.443 a 0.650 a 0.547 a              |
| Mean                | --- 265 B\(^{\ddagger}\) 337 A | --- | 0.396 B 0.612 A | --- |
| LSD\(_{0.05}\)       | --- 25 31 18  | 0.054 0.060 0.030     |                                       |
| Annual total P      |               |                       |                                       |
| Farmlet 1           | 98 85         | 26.5 bc 27.9 c 27.2 c | 0.269 bc 0.330 c 0.300 c              |
| Farmlet 2           | 96 64         | 25.1 c 28.9 bc 27.0 c | 0.261 c 0.452 b 0.357 b              |
| Farmlet 3           | 93 67         | 28.4 b 30.4 b 29.4 b  | 0.307 b 0.453 b 0.380 b              |
| Farmlet 4           | 91 68         | 31.8 a 33.1 a 32.4 a  | 0.348 a 0.484 a 0.416 a              |
| Mean                | --- 27.9 B 30.1 A | --- | 0.296 B 0.430 A | --- |
| LSD\(_{0.05}\)       | --- 2.6 1.5 1.35 | 0.029 0.025 0.017     |                                       |

\(^{\ddagger}\) Farmlet values in each column followed by different lower case letters are significantly different at P < 0.05.

\(^{\ddagger}\) Annual mean values in each row followed by different upper case letters are significantly different at P < 0.05.
Manure application for corn in F2 involved precision positioning of sludge injection furrow near corn row to provide corn P \((35 \text{ kg ha}^{-1})\) and obviate the need for commercial starter fertilizer (Federolf et al. 2016) for juvenile plants sufficient for season-long P supply (Bittman et al. 2012). At this rate of P, the sludge provided \(\sim 224 \text{ kg TN ha}^{-1}\) (115 kg TAN ha\(^{-1}\), tables 1 and 2). Injection reduced ammonia emissions by an estimated \(\sim 30\) to 60 kg N ha\(^{-1}\) compared to conventional broadcasting in F1 (Søgaard et al. 2002, Webb et al. 2010).

### Table 8. Total annual application of P (manure and fertilizer) on silage corn and winter cover crop and crop P uptake and P uptake per applied P across 4 Farmlets in two years

| Management scenario | Total appl. P | Crop P harvested | Annual crop P recovery efficiency |
|---------------------|---------------|------------------|----------------------------------|
|                     | 2017–18       | 2018–19          | Mean                             |
|                     | kg P ha\(^{-1}\) |                  |                                  |
| Corn                |               |                  |                                  |
| Farmlet 1           | 71            | 75               | 29.6 ab a                       |
| Farmlet 2           | 34            | 35               | 28.9 b 42.2 a                   |
| Farmlet 3           | 35            | 35               | 31.0 ab 32.4 b                  |
| Farmlet 4           | 32            | 35               | 33.4 a 40.9 a                   |
| Mean                | 30.7          | 38.4             | 0.416 c                         |
| LSD\(_{0.05}\)       | 4.1           | 5.3              | 0.095                           |
| Relay crop          |               |                  |                                  |
| Farmlet 3           | 15            | 16               | 7.7 a 10.7 a                    |
| Farmlet 4           | 15            | 15               | 8.2 a 9.0 b                     |
| Mean                | 8.0           | 9.8              | 0.531 B                         |
| LSD\(_{0.05}\)       | 0.7           | 1.6              | 0.028                           |
| Corn + Relay Crop   |               |                  |                                  |
| Farmlet 1           | 71            | 75               | 29.6 b 38.3 b                   |
| Farmlet 2           | 34            | 35               | 28.9 b 42.2 b                   |
| Farmlet 3           | 50            | 51               | 38.7 a 40.9 b                   |
| Farmlet 4           | 47            | 50               | 41.7 a 49.9 a                   |
| Mean                | 34.7          | 43.3             | 0.731 B                         |
| LSD\(_{0.05}\)       | 3.8           | 5.2              | 0.07                            |

#### Table 9. Plant crude protein concentration and tissue P concentration for silage corn, winter cover crop and perennial grass across 4 Farmlets and over two years.

| Management scenario | Plant crude protein content | Crop tissue P content |
|---------------------|-----------------------------|-----------------------|
|                     | 2017–18                     | 2018–19               | Mean                      |
|                     | g CP kg\(^{-1}\) DM         | g P kg\(^{-1}\) DM    |
| Corn                |                             |                       |                          |
| Farmlet 1           | 51.1 d                      | 60.7 b                | 55.9 d                   | 1.4 b 2.0 b 1.7 b |
| Farmlet 2           | 57.0 c                      | 62.7 b                | 59.8 c                   | 1.4 b 2.1 b 1.8 b |
| Farmlet 3           | 66.6 b                      | 69.7 a                | 68.1 b                   | 1.9 a 2.2 a 2.0 a |
| Farmlet 4           | 69.8 a                      | 71.9 a                | 70.9 a                   | 1.9 a 2.3 a 2.1 a |
| Mean                | 61.1 c                      | 66.2 a                | 68.1 b                   | 2.2 a 2.2 a 2.1 a |
| LSD\(_{0.05}\)       | 2.9                        | 4.9                   | 2.7                      | 0.1 0.2 0.1     |
| Winter cover crop   |                             |                       |                          |
| Farmlet 3           | 144.5 a                     | 185.5 a               | 165.0 a                  | 2.9 a 4.0 a 3.5 a |
| Farmlet 4           | 140.7 a                     | 163.8 a               | 152.3 a                  | 2.8 a 3.6 a 3.2 a |
| Mean                | 142.6 B                     | 174.7 a               | —                        | 2.9 B 3.8 A —   |
| LSD\(_{0.05}\)       | 8.7                        | 31.5                  | 14.4                     | 0.2 0.7 0.3     |
| Grass               |                             |                       |                          |
| Farmlet 1           | 145.9 b                     | 157.1 b               | 151.5 b                  | 2.7 a 2.4 a 2.6 a |
| Farmlet 2           | 159.9 a                     | 174.9 a               | 167.4 a                  | 2.5 b 2.3 b 2.4 b |
| Farmlet 3           | 133.5 c                     | 144.3 c               | 138.9 c                  | 2.2 c 2.0 c 2.1 c |
| Farmlet 4           | 137.8 bc                    | 142.2 c               | 140.0 c                  | 2.3 c 2.1 c 2.2 c |
| Mean                | 144.3 B                     | 154.6 A               | —                        | 2.4 A 2.2 B —   |
| LSD\(_{0.05}\)       | 10.8                       | 8.7                   | 6.4                      | 0.2 0.1 0.1     |

\(a\) Farmlet values in each column followed by different lower case letters are significantly different at \(P < 0.05\).

\(b\) Annual mean values in each row followed by different upper case letters are significantly different at \(P < 0.05\).

Manure application for corn in F2 involved precision positioning of sludge injection furrow near corn row to provide corn P \((35 \text{ kg ha}^{-1})\) and obviate the need for commercial starter fertilizer (Federolf et al. 2016) for juvenile plants sufficient for season-long P supply (Bittman et al. 2012). At this rate of P, the sludge provided \(\sim 224 \text{ kg TN ha}^{-1}\) (115 kg TAN ha\(^{-1}\), tables 1 and 2). Injection reduced ammonia emissions by an estimated \(\sim 30\) to 60 kg N ha\(^{-1}\) compared to conventional broadcasting in F1 (Søgaard et al. 2002, Webb et al. 2010).
Soil nitrate concentration at V9 averaged 15 mg kg\(^{-1}\) (2018) so 55 kg ha\(^{-1}\) as urea was broadcast between corn rows (as F1) hence the TN applied to F2 corn was 279 kg ha\(^{-1}\) (Zebath et al 2002) There was no significant difference between F2 and F1 for corn yield, grain harvest index, or N uptake but mean N recovery rate and CP concentration was significantly greater for F2 due to a combination of lower N rate and somewhat elevated N uptake (tables 3–6) showing the benefit of sludge placement. Also, as there was no commercial P used in F2, the annual P application rate was about half that in F1 with no loss of yield or P uptake (36 kg P ha\(^{-1}\)) and the F2 P recovery rate was near 100% (versus 46% for F1).

The overall effect of the dual manure stream and band spreading in F2, is a strategic improvement in use of both N and P, with modest additional manure handling cost (settling and decanting, band spreading for grass and precision injection for corn). The added costs are offset by less fertilizer purchase and environmental amenities like less odour, ammonia loss and risk of runoff, although N\(_2\)O emissions from injected slurry may be higher (see Farmlet 3).

**F3: Crop management measures**

F3 uses the nutrient management techniques of F2, and stacks measures to increase production on both corn and perennial grass to increase reliance on homegrown crops and to reduce importation of feeds that contribute to nutrient surpluses. Homegrown feeds should be managed to provide ample balanced nutrients, for example, by avoiding excessive rumen degradable CP which is abundant in intensively managed grass. Increasing feed production may also free up land for new crops.

To increase grass yield, harvest frequency was reduced from 5 to 3x yr\(^{-1}\); the longer growth interval increases mean grass growth rate and Leaf Area Index, and avoids clipping grass soon after stem elongation when plant energy reserves for tillering and root growth are low (Lemaire and Salette 1982). While extending cutting intervals is likely to increase fiber concentration which may reduce milk production, many local dairy farms currently feed purchased straw to increase milk fat.

First harvest for F3 was in late May (mid-heading), about 2–3 weeks after (pre-heading) harvesting for F1 and F2 (Table S1). Mean annual DM yield for F3 was 13.83 t ha\(^{-1}\) compared to 11.20 t ha\(^{-1}\) for F2 (table 5) with the same growing period and nutrient rates which was consistent with preliminary studies at this location (Hunt and Bittman, unpublished data). In both F2 and F3, yields were over 2 t ha\(^{-1}\) greater in 2018 than 2017, due to higher summer and fall precipitation and growth. Spring growth for F3 and F2 averaged 7.85 and 5.49 t ha\(^{-1}\), or 57 and 49% of annual yield, respectively. The delayed spring harvest likely occurs under more favourable harvesting weather (Figure S1). Later and fewer harvests may also reduce soil compaction and labour costs, but harvesting practices may need to be modified (e.g. crimping, tedding).

Despite higher yield, annual N uptake and percent N recovery was similar between F3 and F2, reflecting that the more mature grass in F3 had lower CP and N (29 and 4.6 g kg\(^{-1}\), respectively) than F2 (table 9). N recovery rate in summer was similar for F3 and F2 (34 and 37%), but lower for F3 in spring (42 versus 53%) when it received more N (85 kg ha\(^{-1}\)) for the longer growth period. In fall, much greater N recovery for F3 than F2 (53 versus 28%) due to the greater N uptake and lower application rate suggests less residual soil N when leaching risk is greatest. Relatively low annual N recovery by grass was due largely to over-application of N in 2017 due to summer drought conditions which could not have been predicted. Better long term weather forecasts will help to increase N use efficiency. Unlike N, there was a significant increase (~10%) in P uptake in F3 over F2. In this study, for convenience, the same early maturing tall fescue variety was used for the 5 and 3 harvests. Later maturing tall fescue varieties may be more suitable for the 3-cut system by better maintaining nutritional quality (Koenig and Hunt, unpublished data).

Enhanced corn production was based on using a winter cover crop to reduce fall leaching and to provide additional feed in spring. To advance fall growth, the cover crop was inter-seeded between corn rows at V6 (June 19–21). The cover crop established under the open canopy and persisted in the corn understory so that it was well established at corn harvest. Few effective fall cover crops other than biennial Italian ryegrass can withstand the low light levels, high humidity and dry soil under the corn (Bittman et al 2004, Cordovil et al 2020). Early maturing corn hybrids used in F3 with earlier corn harvesting (11–12 versus 25–27 September) provided additional two weeks of favourable fall growing conditions for boosting N recovery.

The earlier maturing corn hybrid in F3 yielded significantly less (4.6 t ha\(^{-1}\)) than the late maturing hybrid in F2 with the difference greater in 2018 than 2017 (6.0 versus 3.2 t ha\(^{-1}\); table 3). However the spring yield of the relay crop (2.5 t ha\(^{-1}\) in both years) mitigated the differences in crop yields between F2 and F3. The 7% greater harvest index of the earlier hybrid in 2017 added to its feed value, as expected, but hybrids were similar in 2018 and over years (table 4). Corn N uptake was also 23 kg N ha\(^{-1}\) lower in F3 than F2 (table 6). Annual TN recovery (corn plus cover crop) was significantly higher for F3 than F2 thanks to the 70 kg N ha\(^{-1}\) uptake by the relay crop in spring, some of this coming from early-March slurry application of 123 kg N ha\(^{-1}\). Spreading manure on a well established cover crop in early spring frees space for manure storages, and spring applications may have
The results show that incremental improvements in farm production can be made with better management and environmental protection: irrigation and treatment of manure with a nitrification inhibitor (DCD) to mitigate nitrate leaching and N₂O emissions (Cahalan et al. 2015, Di et al. 2007, Ledgard et al. 2014).

Grass yield was 1.1 t ha⁻¹ greater for Farmlet 4 than for Farmlet 3 and this is about an 8% yield increase (table 5) which is consistent with previous irrigation studies (Hunt, unpublished data). Greatest yield for F4 was evident from late-July to mid-October when there is likely to be more response to irrigation and less N₂O emission from manure on grass (Hunt et al. 2019). The increase in N uptake (27 kg ha⁻¹) and N recovery rate of about 55% might be attributed to both factors (table 7). Grass in F4 had the greatest yield, and N and P uptake and recovery among Farmlets (table 6 and 7).

No irrigation was applied to corn in 2017 as the system was not fully installed. There was no significant difference in dry matter yield between F4 and F3 which indicates no yield effect from treating slurry with DCD (table 3). In 2018, corn yield in F4 was significantly higher than F3 but at least 2 t ha⁻¹ lower than F1 and F2. Total annual production, including cover crop, was similar for F4 versus F1 and F2. However, N uptake was 30 kg ha⁻¹ greater for F4, mainly due to the gains in 2018, so mean N recovery for the corn was 72.4% (table 6), which exceeded the grass values. The N uptake and recovery efficiency for corn plus relay crop was significantly greater for F4 than F3.

Whole farm production

Figure 1 shows the effect of varying the proportion of corn and grass area on DM yield, TDN yield and potential milk production per ha, averaged over two years. The comparison between corn and grass can be made because the crops were randomly replicated in a single field with soil suitable for both crops. Under all Farmlets corn yielded per ha more DM, TDN and had higher potential milk production than grass. For the reference F1, corn and grass yield averaged per ha, respectively, 17.4 and 8.0 t DM, 14.0 and 5.7 t TDN, and 31,918 and 14,164 kg milk. At 80 or 100% corn (20 or 0% grass) there was little difference among F1, F2 and F4 although F3 yielded the least due mainly to poor corn production in 2018 (discussed below). Although these production values are indicative of relative farm production, they do not fully describe optimum feeding which requires dairy nutrition modelling to balance rations using specialized supplements. This analysis is underway.

The Farmlet production methods differed in important ways besides production levels. In Farmlet 2–4, corn was produced with no commercial starter N or P using instead precision-placed slurry sludge. A moderate supplement of mineral N fertilizer was added at V9 for all Farmlets but for Farmlets 2–4 the application was based on in-crop soil test. The precision injected sludge in Farmlets 2–4 will have very low ammonia emission which is beneficial but may indeed be subject to greater emissions of N₂O. To mitigate this risk, a nitrification inhibitor (DCD) was added to the manure of both corn and grass (F4) to test mitigation of possible pollution swapping between, in effect, P and N₂O. This has rarely been considered in past research. Early season corn in F3 and F4 showed potential for a higher grain content in 2017, and because of 2-week earlier harvest, will favour a consistently robust fall cover crop that can help soak up soil nitrate (60 kg NO₃–N ha⁻¹ right after corn harvest in mid-September, 2018) to reduce potential nitrate leaching. Also, yield was successfully enhanced by irrigation (F4) and a more consistent feed supply, especially through climate change, is fundamental for producers. High grass yields were achieved with separated slurry applied with a low emission spreader (Farmlets 2–4) and early season manure application in cool spring weather lowers N₂O emissions (Hunt et al. 2019), and lessens late summer applications thus reducing risk of fall and winter leaching (F3 and F4). The Farmlet system facilitates a fair assessment of whole farm crop, animal and environmental performance under novel production methods.

Conclusion

The results show that incremental improvements in farm production can be made with better management practices (BMPs) that, at once, increase farm production efficiency while potentially avoiding nutrient leakage, and that cumulatively the improvements are substantial. Increasing farm nutrient efficiency requires plugging of
Table 10. Plant TDN concentration, TDN Yield and MILK calculation for silage corn, winter cover crop and perennial grass across 4 Farmlets and over two years.

| Management scenario | TDN 2017–2018  | TDN 2018–2019  | Mean  | TDN Yield 2017–2018  | TDN Yield 2018–2019  | Mean  | MILK 2017–2018  | MILK 2018–2019  | Mean  |
|---------------------|-----------------|----------------|-------|---------------------|---------------------|-------|-----------------|-----------------|-------|
|                     | %               |                |       | t ha\(^{-1}\)       | t ha\(^{-1}\)       |       | t ha\(^{-1}\)   | t ha\(^{-1}\)   |       |
| Corn                |                 |                |       |                     |                     |       |                 |                 |       |
| Farmlet 1           | 67.3 b          | 71.6 ab        | 69.5 a| 14.0 a              | 13.9 a              | 14.0 a| 31152 a         | 32685 a         | 31918 a|
| Farmlet 2           | 69.6 ab         | 73.1 a         | 71.4 a| 13.9 ab             | 15.0 a              | 14.4 a| 31409 a         | 35446 a         | 33428 a|
| Farmlet 3           | 70.1 ab         | 71.4 ab        | 70.8 a| 11.7 c              | 10.4 c              | 11.1 c| 27026 b         | 23896 c         | 25461 c|
| Farmlet 4           | 71.2 a          | 70.4 b         | 70.8 a| 12.7 bc             | 12.3 b              | 12.5 b| 29270 ab        | 28052 b         | 28661 b|
| Mean                | 69.6 B          | 71.6 A         | 70.6  | 13.1 A              | 12.9 A              | 13.0  | 29714 A         | 30020 A         | 29867 |
| LSD\(_{0.05}\)      | 3.6             | 2.2            | 2.0   | 1.3                 | 1.3                 | 0.9   | 3293            | 3272            | 2134  |
| Cover crop          |                 |                |       |                     |                     |       |                 |                 |       |
| Farmlet 3           | 57.8 a          | 55.0 a         | 56.4 a| 1.3 b               | 1.2 a               | 1.4 c a| 3978 b          | 3069 a          | 3523 a|
| Farmlet 4           | 57.4 a          | 55.3 a         | 56.4 a| 1.7 a               | 1.1 a               | 1.4 a a| 4373 a          | 2805 a          | 3589 a|
| Mean                | 57.6 A          | 55.2 B         | 56.4  | 1.6 A               | 1.1 B               | 1.4   | 4175 A          | 2937 B          | 3556  |
| LSD\(_{0.05}\)      | 1.7             | 1.1            | 0.9   | 0.1                 | 0.1                 | 0.1   | 244             | 374             | 283   |
| Grass               |                 |                |       |                     |                     |       |                 |                 |       |
| Farmlet 1           | 53.6 a          | 53.7 a         | 53.7 a| 5.3 c               | 6.2 d               | 5.7 d | 13027 c         | 15301 d         | 14164 d|
| Farmlet 2           | 53.7 a          | 54.1 a         | 53.9 a| 5.3 c               | 6.7 c               | 6.0 c | 13221 c         | 16659 c         | 14940 c|
| Farmlet 3           | 52.5 ab         | 52.2 b         | 52.4 b| 6.7 b               | 7.8 b               | 7.2 b | 15744 b         | 18322 b         | 17033 b|
| Farmlet 4           | 51.9 b          | 52.3 b         | 52.1 b| 7.1 a               | 8.4 a               | 7.8 a | 16803 a         | 19817 a         | 18310 a|
| Mean                | 52.9 A          | 53.1 A         | 53.0  | 6.1 B               | 7.3 A               | 6.7   | 14699 B         | 17524 A         | 16112 |
| LSD\(_{0.05}\)      | 1.4             | 0.9            | 0.8   | 0.4                 | 0.4                 | 0.3   | 984             | 1060            | 738   |
| Corn + Cover crop + Grass (50:50 Grass:Corn land ratio) |     |                |       |                     |                     |       |                 |                 |       |
| Farmlet 1           | 63.0 a          | 65.0 a         | 64.0 a| 9.6 b               | 10.1 b              | 9.8 c b| 22089 b         | 23993 bc         | 23041 c|
| Farmlet 2           | 64.3 a          | 65.9 a         | 65.1 a| 9.6 b               | 10.9 a              | 10.2 b| 22315 b         | 26053 a          | 24184 b|
| Farmlet 3           | 62.1 a          | 61.3 b         | 61.7 b| 10.0 b              | 9.7 b               | 9.8 b | 23374 b         | 22643 c          | 23008 c|
| Farmlet 4           | 62.3 a          | 61.4 b         | 61.8 b| 10.7 a              | 10.9 a              | 10.8 a| 25223 a         | 25337 ab         | 25280 a|
| Mean                | 62.9 A          | 63.4 A         | 63.2  | 10.0 B              | 10.4 A              | 10.2  | 23250 B         | 24506 A         | 23878 |
| LSD\(_{0.05}\)      | 2.4             | 1.5            | 1.3   | 0.7                 | 0.6                 | 0.3   | 1643            | 1362            | 1027  |

\(^4\) Farmlet values in each column followed by different lower case letters are significantly different by Fisher’s protected least square difference (LSD, P < 0.05).

\(^b\) Annual mean values in each row followed by different upper case letters are significantly different by Fisher’s protected least square difference (LSD, P < 0.05).

\(^c\) Significant difference between 2-year means of each Farmlet are not shown given Farmlet * year interactions are significant.
nutrient leaks and leaks can only be avoided if nutrient surpluses are reduced, while nutrient surpluses can only be avoided by plugging leaks, according to the ‘hole-in-pipe’ concept (Davidson and Verchot 2000).

Increasing the corn area from the current 40 to 80% of the farm, while including a robust cover crop, increases on-farm feed production with other important consequences. This land allocation, along with F4 practices increased DM yield by 35% and TDN by 40% suggesting that some of the cropland can be repurposed without losing homegrown feed. However, the total N required by the reduced farm crops may be less than the amount excreted by the standard 2.5 milking cows plus replacements per ha (550 kg N ha−1), and the excess N from field applications would increase if measures are taken to reduce ammonia emissions from buildings and storages (Bittman et al 2014). Also, grass crops not only allow for more manure N than corn but also provide a season-long window for spreading manure; if there were just corn and cover crop, all manure would be spread in spring and near year-round storage would be required by farms, which is double current capacities. Other considerations are that corn production is susceptible to poor planting weather and due to sluggish root development in cool spring soils may be sensitive to mid-summer drought often observed on typical well-drained soils. Grass crops can better withstand cool springs though not summer droughts although tall fescue has deeper roots than perennial ryegrass or orchardgrass. Overall crop production on farms with a more even mix of C-4 corn and C-3 grasses may be more consistent. Yield fluctuation, especially under climate change, may be mitigated with corn/cover double cropping, greater use of irrigation, and perhaps planting deeper, rooted crops like alfalfa that have recently proven to be productive and resilient in this region (Bélanger et al 2020).

A benefit of the semi-virtual Farmlet experimental system is that it allows a more complete analysis of implementing BMPs including co-benefits and pollution swapping. The framework allows measures for increasing production to be considered in terms of effects on losses of nutrients, N and P. In this study, precision placement of slurry sludge provided both N and P close to emerging corn roots and obviated the need for starter commercial fertilizer as previously reported (e.g. Bittman et al 2012, Pedersen et al 2020). Commercial starter fertilizer with P and N is currently applied at planting in most corn fields on dairy farms, even those with high soil P, because it improves early growth (Grant et al 2001) and helps overcome damage by tillage to arbuscular mycorrhizae (Bittman et al 2006). Early P also enhances corn maturity, enabling earlier harvest, which benefits growth and N recovery by fall cover crops. The injected sludge has the added benefit of low ammonia loss compared to surface application, but risk of increasing N2O emissions needs to be considered (Webb et al 2010) and adding a nitrification inhibitor to the injected sludge will likely decrease N2O emissions (Chadwick et al 2011) making more acceptable the increased use of corn.

Both increased corn and longer grass cutting intervals lower CP production, which can be provided by high-protein by-products such as soy or canola meals or dry distillers grain. Supplements are formulated to balance rumen-degradable and bypass protein which improves protein utilization. Also, additional protein can be produced by tap-rooted alfalfa and red clover grown on freed-up land, with additional ecosystem benefits like crop diversity and mining for deep soil water in summer and grown in grass mixtures with separated manure solids, may improve field N balances. Since alfalfa has high P uptake, it may help extract soil P and reduce the need for P supplements. Further assessments are needed.

The management expertise and skills needed for the measures used in this study can be considered moderate. There were several practices in our research that could be improved. For example manure separation by settling, while generally successful, can be improved with chemical enhancement (Davidson and Verchot 2000). Relatively late purchase of corn seed in our study limited the choice of more scarce early hybrids and the seed obtained was earlier than desired. The hybrid had little resistance to emerging pest, western corn root worm (Diabrotica virgifera), which struck the early hybrid used in F3 and F4, especially in 2018, contributing to poor corn yields in these plots. Furthermore, tillage used to terminate the cover crop stands in F3 and F4 did not sufficiently break down the sod for corn planting, somewhat reducing corn populations. While tillage options in this trial were limited by space limitation, it can challenge working farms as well. The perennial grass stand in this study was several years old with some encroachment by Ellytrigia repens (L.) Nevski and Alopecurus pratensis (L.) so yields, especially in dry 2017, were lower than typical for good farm fields. But renovation would take the field out of production for a few months, increase emissions of greenhouse gases, and lower potential for building soil organic matter, and the N released by mineralization may exceed the uptake of the seeded crop. Verloop et al (2014) suggested fermenting manure to minimize organic N in soil, but filtering out the liquid fraction may have a similar effect (Zhang et al 2019).

The Semi-virtual Farmlet system provides a method for addressing complex emerging problems and technologies with a system approach. While often omitted from models and top-down global assessments, these types of management issues and challenges are normal for farmers and must be taken into account to realistically interpret farming system metrics such as yield potential and Nitrogen Use Efficiency (Hansson 2008). For example, aggressive pest control or sanguine use of secondary nutrients for the purpose of achieving optimum research results can mislead policy makers and regulators as to what can or should be achieved on farms. On-farm data on nutrient use often fails to address some of the nuances such as pests and the full implications of
adoption of novel strategies and technologies such as farm size, labour and complexity. Successful improvement of complex dairy operations requires ongoing search for knowledge and tools, and equally, farmer skill and motivation for environmental protection must be fostered although these attributes are hard to assess and quantify.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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