Useful performance indicators for improving nitrogen management within grazing-based dairy farms.

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Abstract
Nitrogen (N) inputs are critical for productive and profitable grazing-based dairy systems, but inefficient use can contribute to excess N in the broader environment. Whole-farm N balance (WFNB) provides the commonly used recovery metrics: N use efficiency (NUE), milk production N surplus and N surplus/ha; all recognised as environmental performance indicators. We determined annual WFNB for the Australian dairy industry over a 22 year period, and for a diverse range of 16 commercial dairy farms for the 2013/2014 production year. The industry as a whole demonstrated a long-term declining trend in all N recovery metrics, associated with ongoing intensification. Individual farms in a single production year had a wide variation in NUE, productivity N surplus and N surplus/ha, and a poorly defined relationship between NUE and N surplus/ha. At an industry level, the determination of average farm NUE, milk production N surplus and N surplus/ha provides a useful environmental performance indicator but total industry N surplus needs to be adjusted for changes in contributing land area. For individual farms in any production year, we suggest that in addition to quantifying annual N surplus, employing standardised indices that specifically target key N fluxes and utilisation efficiencies at the component level. These will establish more appropriate industry benchmarks for improving N recovery and inform and improve on-farm N management decisions.

Key Words
Whole-farm nitrogen balance; nitrogen use efficiency; milk production; grazing-based dairy systems

Introduction
Dairy production systems are increasingly challenged with excess nutrients, particularly where nutrient fluxes may be large and incorporation in saleable products is relatively low. Accordingly, the development and implementation of tools and policies that address nutrient imbalances before they become extreme are essential for the long-term sustainability of dairy farming (Cela et al. 2014). A recognised and commonly used approach is the determination of WFNB (Schroder et al. 2003; Gourley et al. 2012a), usually determined over a 12 month period, as it is relatively simple to calculate, relies on readily available farm data, and information generated is easy to communicate to farmers and policy makers. In the case of N, a WFNB relies on determining total N imported and total N exported, generally calculated at the farm scale. Key N recovery metrics generated include N use efficiency (NUE, the ratio of total N output and N input), net farm N surplus (the difference between total N imported and those exported from the farm) and N productivity surplus (net farm N surplus divided by the quantity of agricultural product) (Schroder et al. 2003; Stott and Gourley 2016), all of which are recognised as environmental indicators (Jarvis et al. 2011). This information is increasingly required by global food manufacturers and retailers (Sutton et al. 2013) as evidence of improving nutrient management practices in food production systems.

In this paper we assess the usefulness of N recovery indicators derived from WFNB when evaluating (i) long-term trends in dairy production at an Australian industry level, and (ii) for a diverse range of individual dairy farms within a single production year. We also identify key changes to dairy farming practices due to industry intensification and the potential impacts on N use and recovery, and propose additional farm-based N indicators which provide guidance for improving N management.

Methods
Industry based long-term N balance calculations. Long-term population estimates and average, annual per farm data, quantifying farm size, herd size and dynamics, and mass of key N inputs and N outputs, were sourced from the Australian Bureau of Agriculture and Resource Economics as described by Stott and Gourley (2016). The determination of WFNB followed a commonly used approach modified to suit Australian dairy farm operations (Gourley et al. 2012a) and utilised a calculator developed in MS Excel.

The N inputs and N outputs included standardised estimates of N embodied in various forms of purchased feed (i.e. fodder, concentrates, grains and by-products) and fertilisers, milk sales, animal purchases and sales. Inputs from N fixation and atmospheric deposition were also included. The reported WFNB N recovery metrics involved quantifying total N inputs and outputs for the 'industry average' grazing-based dairy farm.

Farm-based N balance calculations. Whole-farm N fluxes and balances were also determined for 16 diverse dairy farms in Victoria, Australia, using the same standardised WFNB approach, incorporated into a web-based tool as described by Rugoho et al. (2016a). Farms were geographically spread across dairy producing regions and had varying stocking rates, fertiliser inputs, and reliance on imported feed and irrigation, resulting in a broad range of average annual milk production per hectare. A structured questionnaire was used to determine key characteristics of management and gather information on import and export sources of nutrients relevant to the 2013/2014 milking season. Each dairy farm was digitally mapped to determine productivity areas.

Results and discussion

On-going intensification of Australian dairy systems has led to fewer and larger dairy farms with increased stocking rates, greater reliance on imported feed, and higher nitrogen fertiliser use and milk production per cow and per ha. Over this 22 year period, N inputs always exceeded outputs, with inputs growing at a faster rate. N inputs on the average dairy farm increased from 91 to 214 kg N/ha and grew at an annualised rate of around 4%, while N outputs increased from 36 to 57 kg N/ha at an annualised rate of around 2%. The major contributor to total N inputs was bought-in feed, followed by N fertiliser. Milk production consistently made up the bulk (about 90%) of total N outputs. All N recovery indicators deteriorated markedly over the 22 year period suggesting a growing problem in terms of higher losses of reactive N. Whole-farm N surplus for the industry average dairy farm increased from 54 to 158 kg N/ha between 1990 and 2012. NUE declined from 40 to 26%, while milk production N surplus increased from 10.2 to 17.3 g N/l. Total industry N surplus (average N surplus per ha multiplied by the total number of dairy producing hectares) increased from 63,076 to 164,621 t N for the Australian dairy industry as a whole, though the adverse trend moderated somewhat since 2006 (Figure 1) due to an ongoing decline in land used in dairying.

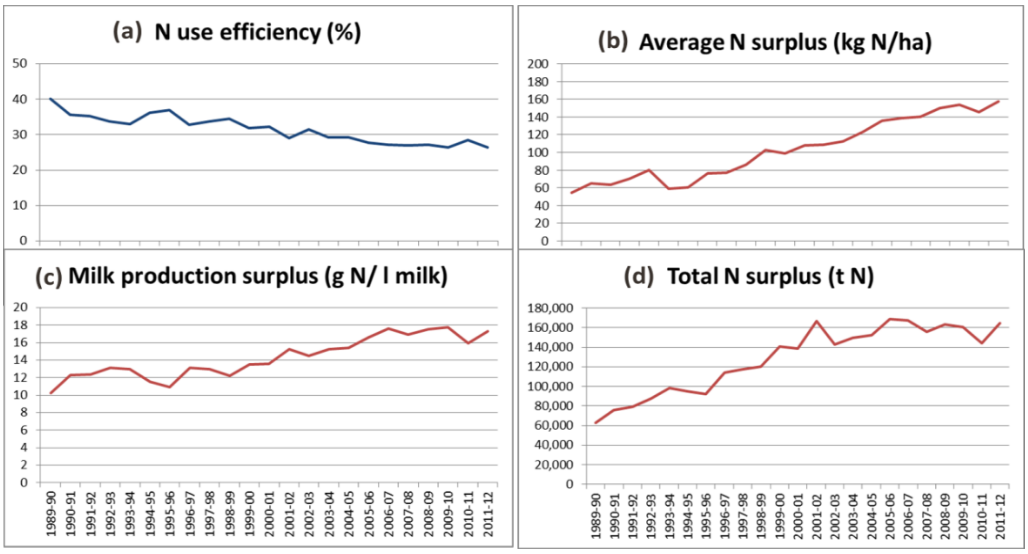

Figure 1. Long-term trends in N use efficiency (a), N surplus (b), milk production N surplus (c) and total N surplus (d), for the average Australian dairy farm between 1990 - 2012. Modified from Stott and Gourley (2016).

The data generated from the 16 case study dairy farms in 2013/14, showed that estimated home grown forage consumed ranged from 5 to 13 t/ha, N fertiliser use ranged from 60 to 400 kg N/ha, and total N imported in feed ranged from 50 - 200 kg N/ha. NUE ranged from 20 to 31%, whole-farm N surplus ranged from 190 to 480 kg N/ha/year and milk production N surplus ranged from 14 to 46 g N/l (Figure 2). These standardised N recovery metrics proved to be comparable to other national and international studies (i.e. Cela et al. 2014; Gourley et al. 2012a), with a strong positive relationship ($P<0.01$) established between whole-farm N surplus and milk production (Figure 2a). In contrast, there were no relationships ($P>0.05$) determined between NUE and milk production, and milk production N surplus and milk production/ha (Figure 2b and 2c), while NUE was a poor predictor of N surplus/ha (Figure 2d).

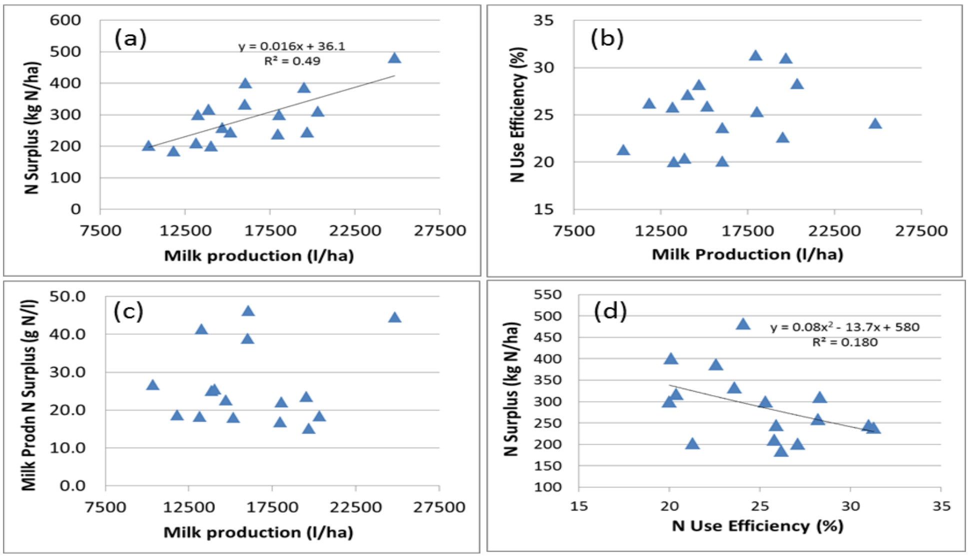

Figure 2. Milk production, N surplus, N use efficiency, milk production N surplus and associated relationships surplus determined for 16 diverse dairy farms.

In an attempt to provide simple environmental indicator, the concept of NUE has been endorsed for a wide range of agricultural systems (Sutton et al. 2013; Oenema 2015). However, as a unit-less indicator, NUE does not estimate any magnitude of N loss and hence possible impact, such as demonstrated by N surplus. Other challenges associated with WFNB relate to varying definitions of system boundaries and unaccounted changes in soil nutrient stores (Godinot et al. 2014), which are particularly relevant for dairy production systems with greater reliance on external feed sources. Moreover, WFNB metrics do not provide guidance to farmers and advisors about opportunities within the current farming system for improved N management practices.

On-farm management strategies that have resulted in reduced N surplus and increased N use efficiency have included more strategic use of inorganic N fertilisers, optimising the recycling of home-produced manure and lowering the N concentration in cow diets (Oenema et al. 2011). The practice of year-round grazing, generally means that only a small proportion of dairy manure is collected in Australian dairy systems (Gourley et al. 2012b). However as stocking rates and reliance on manual feeding systems continue to increase, poor collection and redistribution of manure has the potential to reduce N recycling. Balanced dietary N intakes to reduce excreted N has also be identified, but may be more difficult on grazing-based dairy farms compared to confinement based farms (Gourley et al. 2012b), as pasture with high protien content, often comprises the majority of the diet (Rugoho et al. 2016b). However better balanced diets can result from improved selections of imported feeds. For example, the use of maize silage presents opportunities to better balance energy and crude protein levels (as measured by milk urea N concentrations) and reduce urinary N concentrations.

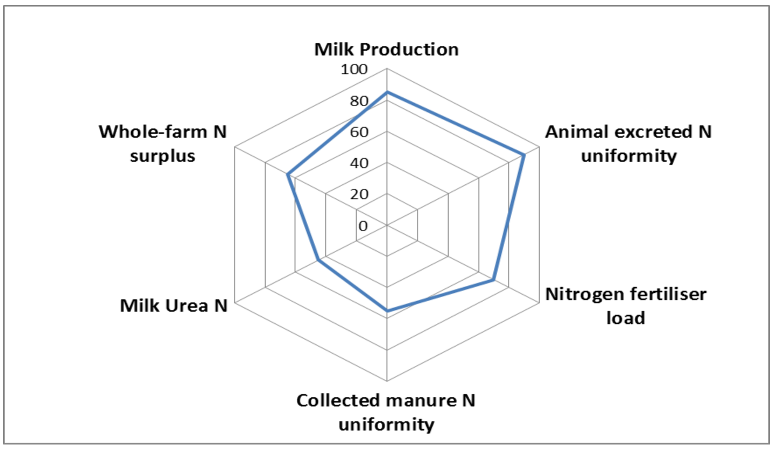

Figure 3. An example of farm and component scale N performance indicators benchmarked against industry standards.

At the industry level, WFNB indicators reflect long-term trends in intensification and have appropriately been used to describe changes in potential environmental impacts. At the individual farm level, WFNB determination of N surplus should be veiwed as a useful assessment for benchmarking individual farm level performance and/or defining threshholds for policy standards. However, the diversity of management practices on grazing-based dairy farms and associated pathways and transformations of N fluxes, highlights the need for additional component-based farm indicators specific to management options and more aligned with impacts. These indicators should be developed along with farmers and industry advisors to meet the duel goals of production and environmental performance, utilise readily available farm-based information and enable bench-marking and guidance for improvement. Such indicators are likely to include whole-farm N surplus, annual N fertiliser loads, spatial uniformity of animal excreted and mechanically distributed manure N loads, and feed N adequecy, as indicated by the example provided in Figure 3.

Conclusion

Whole-farm N balance determination can provide useful performance indicators for grazing-based dairy production, which can be internationally comparable. For the Australian dairy industry, industry average WFNB metrics determined from long-term data has highlighted a continuing decline in N recovery as dairy farms intensify. These indicators can be used to focus industry efforts on increasing N use efficiency and reducing N emissions from dairy farms. However, comparisons of WFNB metrics between individual dairy farms in a single production year are limited, with N surplus the most likely to reflect potential environmental impacts. Further component-based N indicators will provide greater insights into key N fluxes and transformations impacting on N recovery and farm productivity and improve management decisions. Moreover, greater standardisation of within-farm metrics and reporting frameworks are likely to be useful to the broader dairy industry and policy makers, enhancing between farm comparisons, as well as tracking performance improvements over time.

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