FINAL REPORT

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Part 1 - Summary Details

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Project Title: More profit from Nitrogen - Nitrogen use efficiency indicators for the Australian cotton, sugar, dairy and horticulture industries

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Research Program: 2 Industry

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Date submitted: 01 October 2019.-

Part 3 – Final Report

Background

1. Outline the background to the project

There are multiple ways that nitrogen (N) use efficiency (NUE) can be assessed, and NUE indicators are documented in the scientific literature for measuring crop N uptake efficiency, crop N utilization efficiency, and several other agronomic indicators that reflect productivity, profitability and environmental aspects. At present, however, there is no agreement as to how NUE should be calculated and reported across the different agricultural industries in Australia, which makes it difficult to communicate NUE data to stakeholders in a consistent manner. This variation in NUE terminology and definitions also makes it difficult to perform long-term industry-specific assessments of NUE, inform N management practices, and therefore guide future research and development. This project was undertaken to address the lack of standardization of NUE terminology and definitions that is evident in Australia, and specifically in the MPfN Program. As a result, uniform NUE indicators have been now established and they can be applied cross-sector to communicate NUE-related research.

Objectives

2. List the project objectives and the extent to which these have been achieved, with reference to the Milestones and Performance indicators.

Objective 1: Review current metrics used to measure NUE in Australian agricultural systems in such a way that productivity, profitability and environmental aspects are reflected.

Objective 2: Collate input data from the MPfN Program required to calculate the various NUE indicators.

Objective 3: Identify a suite of NUE indicators that are relevant to communicate cross-sector research findings from the MPfN Program.

The three objectives outlined above have been achieved. Metrics used to measure NUE both in Australia and internationally were critically reviewed and documented in this report. From this, a key suite of NUE indicators for assessing productivity, profitability and environmental aspects of N fertiliser use were identified and are proposed for future use industry-wide. The proposed suite of NUE indicators were applied to data derived from the MPfN Program and provided by MPfN Project Leaders, which enabled industry-specific NUE values to be determined. These values were used to compare and contrast NUE between-industries and identify opportunities where NUE could be potentially improved. An NUE indicator framework was adapted for the Australian cotton industry based on a generic framework developed by the EU Nitrogen Expert Panel (2015). A recommendation was subsequently made to apply this concept to other industries as data from the MPfN Program becomes available.

Methods and Results

3. Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research, and

4. Detail and discuss the results for each objective including the statistical analysis of results

The Project Team collected information available in the scientific literature on procedures for measuring and reporting NUE in cotton, grains, sugar, dairy and horticulture systems that was relevant to Australia. Working in collaboration with the MPfN Science Coordinator, Project Leaders and Industry Partners, the Project Team developed cross-sector terminology and definitions of NUE that can be used by the MPfN Program and the wider industries to report NUE data. The MPfN Science Coordinator also requested information from MPfN Project Leaders on indicators used by individual industries to measure NUE and economic return from applied fertilizer N. This information was subsequently consolidated and used to define, describe and interpret guidelines for a suite of cross-sector NUE indicators that are relevant, and can be used, to communicate research findings and implications from the MPfN Program. The following NUE indicators were proposed: (1) fertilizer N utilization efficiency (*NUtE*), (2) fertilizer N uptake efficiency (NU_PE), (3) agronomic efficiency of applied fertilizer N (A_E), and (4) marginal return on applied fertilizer N (MR_F). The calculation, interpretation and cross-industry usefulness of these NUE indicators are presented and discussed. Worked examples are also provided based on data derived from current MPfN Projects.

Outcomes

5. Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.

This project was identified by the MPfN Program team and Industry Partners as necessary to assist with reporting program's outputs and outcomes across industry sectors. Collation and review of available NUE indicators used nationally and internationally, as compiled in this report, will contribute to that effect. Further application of the proposed NUE indicators to the focus agricultural systems of the MPfN Program will enable NUE data to be reported in a standardized manner.

6. Please describe any:

a) technical advances achieved (e.g., commercially significant developments, patents applied for or granted licenses, etc.);

N/A.

b) other information developed from research (e.g., discoveries in methodology, equipment design, etc.); and

Standard terminology and definitions for calculating and reporting N use efficiency.

c) required changes to the Intellectual Property register.

N/A.

Conclusions

7. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

7.1 Fertilizer N uptake efficiency (NU_PE) and soil N supply:

(a) Recovery of fertilizer N as determined by NU_PE was between 28% (sugarcane) to 78% (dairy). The case-studies for cotton reported values of NU_PE that were between 45% (QLD) and 62% (NSW). Soil profile N plus in-season soil N mineralization contributed between 35 (sugarcane) and 210 kg N ha^{-1} (dairy).

(b) There is potential to increase NU_PE in cotton, and this may be achieved by reducing N inputs (without any negative impacts on yield) instead of increased yield. From the literature reviewed, and more specifically from the QLD site, soil N supply explained about 80% of the total N taken-up by cotton. This approach (reduced N inputs) will also reduce the risk of N losses through processes such as denitrification and leaching.

(c) For all crops, there is a need to concurrently manage soil P and K (nutrient interactions), and the soil physical environment, including soil water (or irrigation in irrigated crops), to ensure N uptake and therefore use-efficiency are not adversely affected.

7.2 Economic return from applied N fertilizer:

(a) Much of the variation in average marginal returns between-industries is the consequence of the value of the harvested product in each industry. However, average marginal returns and the marginal return on applied fertilizer N (MR_F) are above the unit cost of N.

(b) Current 'optimum rates' (the N2 rate data in this paper) of the MPfN projects may not have reached point 'C' in Figure 1 indicating there is no economic incentive to reduce N inputs below the N2 rate of the various agricultural systems.

Extension Opportunities

8. Detail a plan for the activities or other steps that may be taken:

(a) to further develop or to exploit the project technology

The conceptual N use efficiency framework proposed for cotton (Figure 4) needs to be verified with 'newer' experimental data derived from work conducted as part of the MPfN Program. The same conceptual approach may be applied to other industries to establish NUE target ranges that are industry-specific. This will also allow for NUE comparisons to be made between-industries.

(b) for the future presentation and dissemination of the project outcomes

The work compiled in this report forms the basis of an intended publication in a scientific journal, and a short article of relevance to practitioners and the industries that are part of the MPfN (e.g., Spotlight) - please refer to point (9) below.

(c) for future research.

It is anticipated that the NUE definitions compiled in this report will be used by MPfN Partners to report and communicate NUE data from their industries.

While common NUE definitions relevant to the MPfN Program were proposed, future examination of industries' NUEs should be undertaken to verify and expand the initial observations conducted as part of this project. The usefulness and robustness of the proposed NUE metrics could be improved by progressively incorporating data produced by the program. Thus, a recommendation is to undertake a retrospect meta-analysis of MPfN NUE to consolidate such data, re-assess NUE indicators, and inform NUE research.

9. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

Journal article: Antille, D. L., Moody, P. W. Nitrogen use efficiency indicators for the Australian cotton, grains, sugar, dairy and horticulture industries. *Environmental and Sustainability Indicators* (In preparation, to be submitted in December 2019).

Dr Moody and Dr Antille will also prepare an article for publication in Spotlight once this report has been reviewed and approved by the project sponsors.

A presentation was delivered by Dr Moody on 5th September 2019 at the 2019 MPfN Partner Forum, and this is available from the MPfN website.

B. Have you developed any online resources and what is the website address?

N/A.

Nitrogen Use Efficiency Indicators for the Australian Cotton, Grains, Sugar, Dairy and Horticulture Industries

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Introduction

More Profit from Nitrogen (MPfN, https://www.crdc.com.au/more-profit-nitrogen) is a four-year cross-industry research program that was established to measure, model and monitor nitrogen (N) use efficiency (NUE) in intensively-managed cropping and pasture systems. The program is financially supported by the Australian Government's Department of Agriculture as part of its Rural Research and Development for Profit Program in collaboration with the Cotton Research and Development Corporation (CRDC), Sugar Research Australia (SRA), Dairy Australia (DA), and Horticulture Innovation Australia (Hort Innovation). For each of these industries, N is a significant input cost to producers and a substantial contributor to environmental footprints.

Collectively, the MPfN Program aims to bring about increased farm profitability and reduced environmental impact by increasing NUE, resulting in a reduction of the amount of N required to produce each unit of product. To achieve improved NUE, the MPfN Program strives to deliver three major outcomes by expanding the knowledge and understanding of: (1) the interplay of soil, weather and climatic, and farm management factors to optimize N rate, timing and placement of application, and N formulation across industries, farming regions, and irrigated and non-irrigated agriculture, (2) the contribution of mineralization of soil organic matter (SOM) to a crop or pasture's N budget, and (3) how enhanced efficiency fertilizer (EEF) formulations can better match a crop or pasture's specific N requirements. The Association of American Plant Food Control Officials (2013) defined EEF as "*fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment (e.g., gaseous losses, leaching or runoff)*". These include controlled release fertilizers (e.g., polymer-coated urea), and slow release fertilizers such as those that are treated with urease (e.g., N-(n-butyl) thiophosphoric triamide) or nitrification (e.g., 3,4-dimethylpyrazole phosphate) inhibitors (Shoji et al., 2001; Halvorson et al., 2014).

Nitrogen usually has a relatively larger effect on crop growth, yield and crop quality than any other nutrient (Goulding et al., 2008). The chart below (Figure 1) shows a generic yield-to-nitrogen response relationship in which there is a maximum agronomic and an optimum economic N application rate; the optimum economic rate generally sits below that required for maximum agronomic yield, depending on the relative value of the crop produce and the unit cost of N fertilizer. From Figure 1, application of N results in increased yield, but above a certain rate that is dependent on crop and soil type, fertilizer form, environmental conditions and general crop husbandry, further additions of N can potentially reduce yield and aggravate problems late in the season such as increased susceptibility to lodging and foliar diseases (e.g., cereals, sugarcane), poor silage fermentation (e.g., fodder crops) or make defoliation (e.g., cotton) rather cumbersome to manage (Singh et al., 2002; Faircloth et al., 2004; Hawkesford, 2014).

Increasing N above the optimum rate also increases the risk of N losses through runoff, leaching and N_2O emissions (Cameron et al., 2013). Such emissions can be exacerbated by surplus N of fertilizer origin (Scheer et al., 2016), and research (e.g., Pittaway et al., 2018) has shown that urea-based fertilizers can stimulate the desorption of soil organic carbon (SOC) from organo-mineral complexes. In irrigated crops, this desorption mechanism can increase the amount of dissolved organic C (DOC) in the irrigation water, which therefore provides a readily available source of C used for microbial denitrification (Weier et al., 1993; Chantigny, 2003). This process, coupled with dissolved (inorganic) N from applied fertilizer, sets the conditions for increased N_2O (and N_2) emissions thereby affecting the overall use efficiency of applied N (Antille, 2018). For irrigated crops (e.g., cotton, sugarcane) that are grown on heavy-textured soils (e.g., >40% clay) these considerations are of importance in practice because of the sustained waterlogged or near-saturated conditions that often occur after irrigation is applied, particularly in surface irrigation systems (Rochester and Constable, 2000; Bange et al., 2004). Therefore, an effective way of managing such losses, and concurrently improving NUE, is by controlling or rather optimizing N inputs (Ringrose-Voase and Nadelko, 2013; Grace, 2016). Generally, a significant change in the value of the crop produce, or equally the cost of fertilizer N, is required to induce large changes in the most economic rate of N (point 'C' in Figure 1); thus, this value tends to change little and can be used as a reliable parameter to inform N decisions (James and Godwin, 2003).

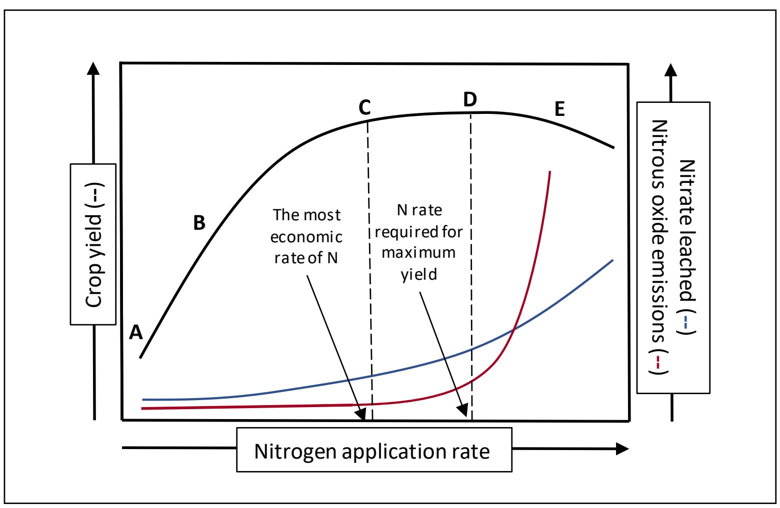

Figure 1. Conceptual diagram showing a typical yield-to-nitrogen (N) response relationship (black curve), and the increased risk of N lost through leaching (blue curve) or nitrous oxide emissions (red curve) when a critical level of N applied as fertilizer is exceeded. Note the non-linear response of soil N_2O to increased N fertilizer rate (after Scheer et al., 2016). Letters show: (A) crop yield as a function of soil N supply, (B) at low N application rates, there is a significant and profitable yield response to increasing rates of N, (C) the most economic rate of N (MERN) denotes the point at which the cost of any additional N is greater than the value of the extra crop yield produced. This N application rate will return the maximum profit from the fertilizer applied. In general, at N rates up to, and including, the most economic (optimum) N rate, there is a roughly constant amount of residual soil N that may be lost by leaching or denitrification (Hong et al., 2007), (D) N application rate required for maximum yield, which is not justified due to loss of economic return from fertilizer applied, and (E) yield or crop quality penalties may occur and thus profit margins. At this point, there is also an increased risk of environmental losses of N due to proportionally larger surplus of applied N (modified from DEFRA, 2010).

The efficiency of fertilizer N-use in Australia is considered to be low, particularly in arable cropping. For example, for irrigated cotton, apparent above-ground recovery of fertilizer N averages ≈40% (Macdonald et al., 2015, 2017), but this can be lower in dryland cropping systems such as wheat with mean apparent N recoveries of around 35% (Angus and Grace, 2017). The rest of the N applied as fertilizer may be stored in soil or lost through one or more processes such as leaching, runoff or gaseous evolution (e.g., Silburn et al., 2013; Grace, 2016). Recent research (e.g., Scheer et al., 2013; Macdonald et al., 2016) has shown that these losses of N are significant, both from the environmental and economic perspectives. Fertilizer experiments (n=74) using ^{15}N on wheat crops in Australia have also shown that total N recovered at maturity was about 45% in above-ground biomass, 35% in soil and 20% was not recovered suggesting that this N was lost to the environment (data compiled by Angus and Grace, 2017 from multiple sources). Similar observations (fertilizer N recovered in crop ≈40%) were also reported by Chen et al. (2008) for cereal crops grown in Australia. Key factors affecting the efficient use of N from applied fertilizer are (after Johnston and Poulton, 2009): (1) crop N demand and crop variety, (2) soil organic matter, (3) plant availability of soil phosphorus (P) and potassium (K), and (4) the soil physical environment (Wolkowski, 1990; Lipiec and Stępniewski, 1995). Thus, care should be taken to ensure that these factors are concurrently managed to ensure N uptake and use efficiency are not affected.

When reporting about use efficiency of applied N in fertilizer and organic materials, the extent to which N is recovered is a consequence of the definition of NUE adopted and whether crop yield, N uptake or other data are used. However, it is generally agreed that a 'large' percentage recovery of applied N reflects an 'efficient' use of that N by the crop (Hawkesford, 2014). There are multiple ways that NUE can be assessed, and NUE indicators are documented in the scientific literature for measuring crop N uptake efficiency, crop N utilization efficiency, and several other agronomic indicators that reflect productivity, profitability and environmental aspects (e.g., Dobermann, 2007). At present, however, there is no agreement as to how NUE should be calculated and reported across the different agricultural industries in Australia, which makes it difficult to communicate NUE data to stakeholders in a consistent manner. This variation in NUE terminology and definitions also makes it difficult to perform long-term industry-specific assessments of NUE, inform N management practices, and therefore guide future research and development. Given this lack of standardization of NUE terminology and definitions that is evident in Australia, and specifically in the MPfN Program, there is a need to agree on uniform NUE indicators that can be applied cross-sector to communicate NUE-related research.

The work reported in this paper reviews the procedures used in Australia for measuring and reporting NUE in cotton, grains, sugar, dairy and horticultural systems. This work was undertaken in consultation with the MPfN Science Coordinator and MPfN Project Leaders to develop cross-sector terminology and definitions of NUE that could be used by practitioners to record NUE data. This information was subsequently consolidated into this cross-sector document so that it can be used to report and communicate NUE findings and implications.

OBJECTIVES AND SCOPE

The specific objectives of this study were to:

(1) Review current metrics used to measure nitrogen use efficiency in Australian agricultural systems in such a way that productivity, profitability and environmental aspects are reflected,

(2) Collate input data from the MPfN Program required to calculate the various NUE indicators, and

(3) Identify a suite of NUE indicators that are relevant to communicate cross-sector research findings from the MPfN Program.

There was a requirement for NUE definitions available in the literature and NUE indicators that are in common use in Australian agricultural systems to be discussed with MPfN Project Leaders and Industry Partners, and subsequently documented for future use industry-wide. This project was identified by the MPfN Program team and Industry Partners as necessary to assist with reporting the program's outputs and outcomes across industry sectors. The considerations for measuring and reporting NUE addressed in this work are relevant in the current scenario as all industries involved in the MPfN Program, as well as the grains industry, are committed to increasing profitability while reducing the environmental footprint of both N and water use by crops (e.g., Roth et al., 2013; Kirkegaard et al., 2014; Hedayati et al., 2019; Powell et al., 2019).

OUTLINE METHODOLOGY

The Project Team collected information available in the scientific literature on procedures for measuring and reporting NUE in cotton, grains, sugar, dairy and horticulture systems that is relevant to Australia. Working in collaboration with the MPfN Science Coordinator, Project Leaders and Industry Partners, the Project Team developed cross-sector terminology and definitions of NUE that can be used by the MPfN Program and the wider industries to report NUE data. The MPfN Science Coordinator also requested information from MPfN Project Leaders on indicators used by individual industries to measure NUE and economic return from applied fertilizer N. This information was subsequently consolidated and used to define, describe and interpret guidelines for a suite of cross-sector NUE indicators that are relevant, and can be used, to communicate research findings and implications from the MPfN Program. These NUE indicators aim to reflect profitability, productivity and environmental outcomes. A presentation with preliminary outcomes of this work was delivered by Dr Philip Moody at the 2019 MPfN Partner Forum held in the Gold Coast on 5th September 2019, and it was well received by project partners from the cotton, sugar, dairy and horticultural industries.

Objective 1: Review current metrics used to measure nitrogen use efficiency in Australian agricultural systems

This section presents the various NUE indicators provided by Project Leaders, which are therefore industry-specific. Inevitably, there is some overlap in the terminology used and the proposed NUE definitions, but all indicators are quoted as reported by Project Leaders. Relevant NUE indicators are later collated in Tables 7 and 8, and these consist of a set of NUE metrics that are recommended for future use at industry-level. MPfN Project Leaders and their teams contributed to this project objective through the provision of NUE indicators and data relevant to the corresponding industries.

Agronomic Indicators

Cotton

The most commonly used NUE indicators in the Australian cotton industry are shown in Equations (1) to (4), and consist of the following: N fertilizer use efficiency, internal N use efficiency, apparent N fertilizer recovery, and apparent N recovery in cottonseed, respectively (after Rochester, 2011, 2012; Antille, 2018; Macdonald et al., 2018):

$$NFUE = \frac{L_N}{N_R} \quad (1a)$$

where: *NFUE* is N fertilizer use efficiency, L_N is lint yield (kg ha^{-1} lint) of the crop fertilized with N ($N \neq 0$), and N_R is N application rate (kg ha^{-1} N). If lint yield for a zero-N cotton crop was available, Equation (1a) can be written as:

$$NFUE = \frac{(L_N - L_{N=0})}{N_R} \quad (1b)$$

where: $L_{N=0}$ is lint yield (kg ha^{-1} lint) of the crop without fertilizer N, and all other variables are as defined in Equation (1a).

$$iNUE = \frac{L_N}{U_N} \quad (2)$$

where: *iNUE* is internal N use efficiency, also referred to as 'physiological use efficiency of applied N', L_N is lint yield (kg ha^{-1} lint), and U_N is N uptake of the fertilized crop. Uptake is derived from the concentration of N in plant (%, $^{w}/_{w}$) prior to defoliation and total above-ground biomass (kg DM ha^{-1}),

$$ANFR = \frac{(U_N - U_{N=0})}{N_R} \quad (3)$$

where: *ANFR* is apparent N fertilizer recovery, U_N and $U_{N=0}$ are N uptake by crops with and without applied N, respectively, and N_R is N application rate, all in kg ha^{-1}, and

$$ANFR_{CS} = \frac{(CS_N - CS_{N=0})}{N_R} \quad (4)$$

where: $ANFR_{CS}$ is apparent N fertilizer recovery in cottonseed, CS_N and $CS_{N=0}$ are cottonseed-N of the crop with and without applied N, and N_R is N application rate, all in kg ha^{-1}.

Cottonseed-N is derived from total N in seed (%, $^{w}/_{w}$) and seed yield (kg ha^{-1}). Equation (4) was used by Antille (2018) who assessed N use efficiency in fertigated cotton crops and subsequently related N recoveries in cottonseed to Rochester's (2012) critical cottonseed-N value (3.53 ± 0.21% N, $^{w}/_{w}$). Under the Australian conditions, and for irrigated cotton, this critical value denotes the cottonseed-N concentration when the N application rate to the crop has been optimized. An increment of approximately 0.1% N concentration in cottonseed above the value recommended by Rochester (2012) denotes an excess of fertilizer-N applied of about 20 kg ha^{-1} N, which can be used to inform N decisions in subsequent seasons.

GRAINS

While grains are not part of the MPfN Program, NUE metrics used in the Australian grains industry are included in this work for the sake of completeness and to enable cross-comparison with relevant metrics used in other industries. 'Grains' are referred to here as non-legume crops. The set of NUE indicators reported here are based on earlier work (Cassman et al., 1998; Baligar et al., 2001; Johnston and Poulton, 2009), and comprise of two methods; namely, the direct and difference methods, respectively.

Direct method. This method uses ^{15}N, which allows measuring N in the growing crop, and crop residues after harvest as well as the harvested product. Residual ^{15}N in soil at harvest can also be measured. Results are usually expressed in percentage, and if measured in all plant and soil components, partitioning is possible. The direct method can provide accurate estimates of NUE, but it is expensive due to the cost of N labelling.

Difference method. This method requires that treatments in the same experiment have and have not been applied with N fertilizer. The result obtained with this method is influenced by the rate of N applied, the yield achieved, the experimental conditions of the site (e.g., pressure from weeds, diseases), and more generally by *Genetics* × *Management* × *Environment* interactions. As applied N increases above the rate required for maximum yield, yield tends to decrease (Figure 1), but grain-N would tend to increase (Benzian and Lane, 1979, 1981). Despite this, the increase in grain-N is not sufficient to prevent percent N recovery decreasing with increasing rate of applied N (Johnston and Poulton, 2009). Data obtained with the difference method may be then used in two ways, as follows:

(1) Using N uptake. This method is regarded as the 'apparent recovery' (A_R) or 'apparent efficiency' of applied N, thus:

$$A_R = \frac{(U_N - U_{N=0})}{N_R} \qquad (5)$$

where: U_N and $U_{N=0}$ are total N uptake in above-ground crop biomass (kg ha^{-1} N) corresponding to the treatment ($N \neq 0$) and control ($N = 0$), respectively, and N_R is N application rate (kg ha^{-1} N) for a specified N source (e.g., urea). Uptake 'U' is obtained as follows: $U = N_{TB} \times TB$, where N_{TB} is N concentration in total above-ground biomass (%, $^{W}/_{W}$), and TB is total above-ground biomass (kg ha^{-1}), respectively.

(2) Using crop yield. This method is regarded as the 'agronomic efficiency' (AE) of applied N, thus:

$$A_E = \frac{(Y_N - Y_{N=0})}{N_R} \qquad (6)$$

where: Y_N and $Y_{N=0}$ are the yields of harvested product (kg ha^{-1}) corresponding to the treatment ($N \neq 0$) and control ($N = 0$), respectively, and N_R is N application rate (kg ha^{-1} N). Equation (6) is equivalent to Equation (1b) used in cotton.

The 'apparent recovery' method may also be used to report N recovered in grain, but this needs to be specified when reporting NUE if recovery is only 'in grain' or 'in grain plus straw', that is, N recovered in total above-ground biomass. Equation (5) can be expressed as a partial N balance ($PNB = \frac{U_g}{N_R}$), which is N recovered in grain (U_g, where: $U_g = N_g \times Y$) in relation to N applied as fertilizer, and denotes the removal-to-use ratio (Norton, 2017).

Two other NUE indicators are also used in grain crops; namely: the partial factor productivity of applied N and the physiological efficiency of applied N, respectively. These are shown below (after Johnston and Poulton, 2009):

(1) Partial factor productivity of applied N. The ratio between kg of product obtained per kg of N applied, thus:

$$PFP_N = \frac{Y_N}{N_R} \qquad (7)$$

where: Y_N and N_R were defined above, all in kg ha^{-1}. Equation (7) is equivalent to Equation (1a) used in cotton.

(2) Physiological efficiency of applied N (or of N use). The ratio between kg of product increase per kg increase in N in the crop, thus:

$$PE_N = \frac{(Y_N - Y_{N=0})}{(U_N - U_{N=0})} \quad (8)$$

where: Y_N, $Y_{N=0}$, U_N and $U_{N=0}$ were defined above, all in kg ha^{-1}. Equation (8) is similar to Equation (2) used in cotton, except that *iNUE* does not consider $L_{N=0}$ and $U_{N=0}$ in its calculation.

In the absence of water stress, satisfactory grain yield and grain-N can be achieved when N availability, both from soil and fertilizer, does not limit N uptake by the crop and its subsequent translocation to grains (Sadras and Lawson, 2013). Cereal crops will first use N to increase leaf canopy, which will determine the rate of accumulation of sugars and the amount produced. In early stages of plant growth, the number of tillers will be determined, and the number of grains per ear will be set (Fischer, 2011). Grain yield will increase if there is sufficient assimilate to be translocated to this predetermined number of grains (Slafer and Andrade, 1993). Nitrogen taken-up by the plant and not used for proteins formation will be stored in the plant and re-mobilized to grains during the grain filling phase (Angus and Fischer, 1991). Generally, the yield response to N up to a rate of about 300 kg ha^{-1} is non-linear for grain crops (e.g., wheat) and linear for grain-N (Benzian and Lane, 1979, 1981). A decline in PE_N suggests that the plant has diverted proportionally more N to grains to increase protein content with increasing N applied as fertilizer (Johnston and Poulton, 2009).

Grain-N is an important consideration from the quality perspective of winter cereal crops, and it will also affect NUE because of the way this is calculated (Gashawbeza et al., 2003). Target grain-N content for feed wheat varieties is 2% N (w/w, or 2.2% for bread-making varieties), and in high-yielding wheat this may be adjusted by increasing or decreasing the N applied as fertilizer by 30 kg ha^{-1} N for every 0.1% N (w/w) content in grain below or above the target grain-N content, respectively (DEFRA, 2000). Dilution effects may occur when there is a rapid increase in grain yield after adding a relatively small amount of N (e.g., from 0 to 50 kg ha^{-1} N), which results in reduced N concentration in grain compared to a crop grown in the absence of N application (Benzian and Lane, 1979, 1981). Other studies (e.g., Boquet and Johnson, 1987; Vaidyanathan et al., 1987) have shown that grain protein content was not affected by N application rates in the range of 0-100 kg ha^{-1}, but total protein content per hectare increased significantly due to increased grain yield. Johnston and Poulton (2009) also indicated that the percent recovery of each increment of applied N is sometimes determined; on the near-linear part of the yield-to-nitrogen response curve, N recovery (%) of each increment of N will be similar, but as the yield approaches the maximum, N recovery (%) of each additional increment of applied N will tend to decrease rapidly.

SUGAR

A review of N use efficiency in the Queensland sugar industry (Bell et al., 2014) was undertaken to benchmark NUE and to identify strategies for improving NUE in situations where low efficiency was identified. Table 1 indicates the NUE indicators used to describe the NUE of the sugarcane cropping system. These indicators are based on those described in Ladha et al. (2005).

Table 1: Terminology and acronyms used in the quantification of sugarcane crop responses to applied N fertilizer (after Bell et al., 2014).

Description	Unit	Acronym
N utilization efficiency: the efficiency with which a crop utilizes accumulated N to produce a unit of crop growth.	t DM kg^{-1} crop N	NU_tE
Fertilizer N uptake efficiency: the efficiency with which applied N fertilizer is accumulated in crop biomass.	kg crop N kg^{-1} fertilizer N applied	NU_PE_{FERT}
Agronomic efficiency of fertilizer N: the efficiency with which fertilizer N is used to produce crop yield.	t cane yield kg^{-1} fertilizer N applied	AE_{FERT}
Apparent agronomic N use efficiency: the apparent efficiency with which fertilizer N is used to produce crop yield, without taking account of the cane yield produced when no N fertilizer N has been applied.	t cane yield kg^{-1} fertilizer N applied	$AppAgronEff$

Because of its ease of calculation, the index *AppAgronEff* has been widely used in the sugar industry to measure NUE. The industry's best management practice (BMP) guidelines, SIX EASY STEPS (Schroeder et al., 2010), use its reciprocal value to estimate crop N requirements: 1.4 kg applied N/t cane to 100 t cane/ha, and then 1 kg applied N/t cane thereafter. However, this index does not take account of the cane yield that would have been produced without any added N fertilizer, and nil applied N cane yields collated from published data in Table 2 of Bell et al. (2014) ranged from 60 to 115 t cane/ha for plant crops and from 20 to 95 t cane/ha for ratoon crops. It is apparent that, despite its simplicity, *AppAgronEff* may lead to misleading perceptions of NUE. Consequently, NU_PE_{FERT} and AE_{FERT} are now being used in sugarcane research field trials to benchmark NUE, and come with the necessary input data requirement of either having a measure of above-ground crop N uptake and biomass at nil applied N, or above-ground crop N uptake and biomass for two rates of fertilizer N addition.

It is important to note that almost the entire body of fertilizer N rate research in the Queensland sugar industry has been carried out using urea as the N fertilizer form. Simulation modelling results presented in Thorburn et al. (2014) demonstrate the susceptibility of N applied as urea, following its rapid conversion to nitrate-N, to loss by the pathways of leaching, denitrification or runoff, depending on the hydraulic characteristics of the soil, its position in the landscape, and seasonal rainfall conditions. Because the collated values of NU_PE_{FERT}, AE_{FERT}, and *AppAgronEff* presented in Bell et al. (2014) are almost entirely based on urea as the N fertilizer, it can be assumed that when N is applied in an enhanced efficiency fertilizer (EEF) form (e.g., urea plus nitrification or urease inhibitors; controlled release coated fertilizers), the measured values of these NUE indicators may change relative to the same rate of N applied as urea.

Where EEFs can mitigate nitrate-N losses by prolonging inorganic N in the ammonium-N form and/or better synchronization of inorganic N release from fertilizer with crop N demand, the opportunity may exist for reducing N application rate without adversely affecting production, and this principle is currently being investigated in field trials being undertaken in the National Environmental Science Program Project 2.1.8: Improved Water Quality Outcomes from On-Farm Nitrogen Management (https://www.environment.gov.au/science/nesp/hub-tropical-water-quality). The outcome of improved NUE via sustained productivity at reduced applied N rates will have beneficial effects on water quality and greenhouse gases mitigation. However, the economic impact of using EEFs rather than the less expensive urea fertilizer will also require assessment.

DAIRY

The MPfN dairy team recommends that the following NUE indicators be used when communicating NUE concepts to industry and the farming community:

$$Average\ NUE = \frac{(DM_N - DM_{N=0})}{N_R} \qquad (9)$$

where: DM_N and $DM_{N=0}$ are dry matter (DM) yield of grass crops with and without applied N, and N_R is N application rate, all in kg ha^{-1}. The average NUE is expressed as kg DM kg^{-1} N applied and is comparable to 'A_E' defined for grains (Equation 6). This index is useful to understand the profitability of using N relative to other purchased feed options in dairy systems.

$$Marginal\ NUE = \frac{(DM_{N(x)} - DM_{N(x-1)})}{(N_{(x)} - N_{(x-1)})} \qquad (10)$$

where: $DM_{N(x)}$ and $DM_{N(x-1)}$ are dry matter yield (DM) of two incremental N application rates; namely, $N_{(x)}$ and $N_{(x-1)}$, respectively, all in kg ha^{-1}. Marginal NUE is expressed as kg (additional) DM kg^{-1} N applied. This index is useful to understand the profitability of successive or incremental N applications.

Both the above NUE indicators are useful when employed in conjunction with look-up tables of likely responses to applied N fertilizer in each month of the year. The dairy team indicated that these tables should be updated for the Australian dairy regions of Victoria and Tasmania, and developed for New South Wales. They also commented that look-up tables should be based on 'low', 'medium' and 'high' potential indicative of water, potential mineralization of soil organic N, species composition of the pasture and basal fertility of soil.

Other indicators of NUE proposed by the MPfN Dairy Group are:

$$N\ surplus = N_i - N_O \qquad (11)$$

where: N surplus is the difference between total N inputs (N_i) and total N outputs (N_O), which includes outputs in meat and milk and is derived from a farm-wide N balance. This index can be used to reflect N loading on-farm and therefore N loss potential.

$$Apparent\ N\ recovery = \frac{Grass\ N\ uptake}{N_i} \qquad (12)$$

where: grass N uptake is derived from DM yield (kg ha^{-1}) and N content (%, $^{w}/_{w}$) in harvested plant material, and N_i is total N inputs (kg ha^{-1}). This index denotes the total N removed from the pasture system in a given time period as a function of total N input, and is expressed as a percentage.

De Klein et al. (2017) define this NUE metric as N harvested in pasture and expressed as a percentage of the total N input to the pasture from fertilizer, manure, atmospheric deposition, soil N supply and N fixation sources. Bittman et al. (2016) used a whole-farm NUE value, which was defined as N removed in end-products as a percentage of all 'purchased' N. Therefore, the metric adopted by Bittman et al. (2016) does not consider N inputs such as atmospheric deposition and biological fixation. De Klein et al. (2017) also suggested that in addition to the apparent or '*relative*' NUE defined above, N surplus can be used as an '*absolute*' indicator (kg N ha^{-1} $year^{-1}$) of NUE. Nitrogen surplus is simply the difference between total N inputs and total N outputs (De Klein et al., 2017), which is the approach proposed by the EU Nitrogen Expert Panel (2015).

Apparent N recovery can be 100% when mineralization contributes significantly to the system. The actual N recovery in plant derived from ^{15}N data (direct method) is not commonly used with farmers, but it can be used to provide accurate estimates of the actual fertilizer N recovery in pasture systems.

HORTICULTURE

The NUE indicators proposed by the MPfN Horticulture group are specific for (perennial) deciduous fruit trees such as mango and cherry, and may not be applicable to other horticultural crops, which were not within the scope of this work. There are several NUE indicators reported in the horticulture literature and used by practitioners, but most of them have been developed for annual crops and therefore have limited focus on perennial crops. The following NUE indicators were proposed (after Fixen et al., 2015):

$$PFP_N = \frac{Fruit\ yield\ per\ tree}{N_R} \qquad (13)$$

where: PFP_N is the partial factor productivity of applied N fertilizer (kg kg^{-1} per tree), which is derived from fruit yield per tree (fresh weight, kg) and N application rate per tree (kg).

The PFP_N can be easily calculated with a grower's record that has historic N inputs and individual yield of trees, and it may be used as a long-term indicator of trends at the paddock or farm scales. Given that Equation (13) is calculated based on fresh yield, changes in fruit water content at the time of harvest will significantly affect PFP_N. Thus, the calculation of PFP_N may be standardized by using DM yield instead of fresh weight.

$$PNB = \frac{N_{FRUIT}}{N_R} \tag{14}$$

where: PNB is partial N balance (kg kg^{-1}), N_{FRUIT} is N removed in fruit per tree (kg) and N_R is the N application rate (kg) per tree. N_{FRUIT} is estimated from the mean N concentration in fruit (%, $^w/_w$) and the total fruit DM (kg) per tree. Nitrogen concentration in fruit needs to be determined from at least three (n=3) bulked samples of fruit per tree containing equal numbers of subsamples of fruits from the lower, middle and upper parts of the tree.
PNB measures the relationship between N removed from the tree (in fruit) and N applied as fertilizer, that is, a ratio of N output to N input. It does not consider the contribution of N from soil or re-mobilization of N stored in vegetative or other parts of the tree. Whilst the above measurements are easily determined through simple record-keeping and standard fruit N analysis testing, for research purposes, a more thorough assessment of NUE can be achieved using ^{15}N.

The N uptake efficiency, also referred to in the horticulture industry as 'apparent recovery efficiency', is shown in Equation (15) below (after Neilsen et al., 2001; Fixen et al., 2015):

$$NU_PE = \frac{U_N}{N_R} \tag{15}$$

where: NU_PE is N uptake efficiency (kg kg^{-1}), U_N is N uptake by the tree (kg) with applied N fertilizer, and N_R is N application rate per tree (kg). Nitrogen uptake in a tree is derived from the above-ground DM of the tree (kg) and the N concentration (%, $^w/_w$) in the above-ground DM.

The above index provides an estimate of the amount of N applied as fertilizer taken-up by the fruit tree. If a zero-N treatment was available, then $U_{N=0}$ (uptake from an unfertilized tree crop) can be subtracted from U_N to determine the 'apparent recovery efficiency by difference', which provides an indication of response to applied fertilizer N. Potential N losses from the system and the efficiency of management practices may also be inferred when NU_PE is determined by the difference method (Fixen et al., 2015). This measurement does not distinguish between N used for vegetative growth and fruit production. Because (perennial) deciduous trees recycle N between-seasons, it is important to quantify how much of the applied N in the current season contributes to the overall N makeup of the tree as measured by whole-tree biomass excavations when trees are dormant.

The internal utilization efficiency (Equation 16) reflects the ability of the tree to transform N taken-up from all sources into yield, thus:

$$iNUE = \frac{Fruit\ yield\ per\ tree}{U} \qquad (16)$$

where: *iNUE* is internal N use efficiency, *fruit yield per tree* was defined in Equation (13) and should be expressed as DM yield (kg) and U is total N uptake in above-ground tree biomass with N applied (kg). Uptake 'U' is derived from the N concentration in above-ground tree biomass (%, $^{w}/_{w}$) and total above-ground tree biomass (kg). Equation (16) is comparable to Equation (2) used for cotton.
This index can be used to determine the partitioning to fruit of N taken-up by the tree, but comparisons in *iNUE* between-seasons may not be possible as total N in fruit varies significantly with tree load, fruit set and thinning, and N storage and re-mobilization from previous seasons. This internal N dynamics is particularly important in fruit trees with biennial bearing tendencies such as apples (Nannipieri et al., 1995). However, it is possible to substitute fruits with other organs of the tree or to compare partitioning between tree parts using this dataset.

The MPfN Horticulture Group recommends the use of *NU_PE* and *iNUE* as these two indices provide reliable estimates of N uptake by the fruit tree within a season and the N partitioned into fruit for fruit production, respectively.

ECONOMIC INDICATORS

A very simplistic economic indicator of NUE is Marginal Return ($ return /$ N fertilizer cost) and the cross-industry figures for this indicator based on data requested from the individual MPfN projects are collated in Table 8. However, a more rigorous economic definition is possible (and highly desirable) across industries, and such an indicator is outlined below.

DEFINING THE MOST ECONOMIC RATE OF NITROGEN

The approach described here can be used to determine the Most Economic Rate of Nitrogen (MERN) and is applicable to situations where the yield-to-nitrogen response relationship can be described by fitting a nonlinear (quadratic) function (Equation 17) to the data. This approach (Equations 17 to 22) is based on earlier studies (James and Godwin, 2003; Kachanoski, 2009) dealing with cereal crop responses to applied N fertilizer, and assumes a quadratic-plateau relationship, as follows:

$$y = a + bx - cx^2 \qquad (17)$$

where: a, b, and c are regression coefficients, x is N application rate, and y is yield. The lowest N application rate at which the maximum yield is obtained is derived by equating the first order differential to zero (Equations 18 and 19):

$$\frac{dy}{dx} = b - 2cx' = 0 \quad (18)$$

therefore,

$$x' = \frac{b}{2c} \quad (19)$$

where: x' is the (lowest) N application rate at which the maximum yield (Y_{MAX}) is obtained, and where $x \leq x'$. The N rate corresponding to x' is referred to as N_{MAX}. Subsequently, the most economic rate of N (*MERN*) is obtained when the differential is equated to the price ratio (P_R), as follows:

$$b - 2cx' = P_R \quad (20)$$

and,

$$P_R = \frac{P_N}{P_C} \quad (21)$$

therefore,

$$MERN = \frac{b - P_R}{2c} \quad (22)$$

where: P_R is price ratio, P_N is price of N fertilizer (AUD kg^{-1}), P_C is price of the crop (AUD kg^{-1}), and MERN is the most economic rate of N application (kg ha^{-1}) for a given price ratio P_R.

Price ratio and MERN calculations should be based on P_N and P_C for the corresponding year of harvest. Price ratio is equivalent to the break-even ratio and indicates the extra return of the crop produce that just covers the extra unit of N added. At this point, the economic return from N applied as fertilizer is maximized. The yield that is achieved with an N input equivalent to MERN corresponds with point 'C' in Figure 1.

OBJECTIVE 2: COLLATE INPUT DATA REQUIRED TO CALCULATE NUE INDICATORS

COTTON

Data for cotton were sourced from experimental sites located in northern New South Wales (Schwenke, 2019, *pers. comm.*) and southern Queensland (Scheer et al., 2018). At the Queensland sites, cotton was grown under furrow and overhead irrigation over two consecutive seasons (2015-2016 and 2016-2017) as shown in Table 2 below. The data from New South Wales are for a furrow irrigated cotton crop grown at Narrabri during 2017-2018 with urea applied sub-surface.

Table 2: Data collated for irrigated cotton from northern NSW (Schwenke, 2019, *pers. comm.*) and southern QLD (Scheer et al., 2018). 'Query' refers to data requested from MPfN Project Leaders. Above-ground biomass and above-ground biomass-N do not include lint and seed yield, and lint-N and seed-N content, respectively, which are considered separately. Fertilizer + application cost is the cost of urea applied in shallow (150 mm deep) subsurface bands, and gross margin is the difference between gross income and fertilizer cost for the year of harvest. (---) means data not available. The cropping season for cotton is 6 months.

Location	---	Northern NSW			Southern QLD, Furrow			Southern QLD, Overhead		
Query	**Unit**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**
Fertilizer rate	kg N ha^{-1}	0	112	292	0	125	180	0	125	180
Yield (lint)	kg ha^{-1}	2742	3617	3733	2406	3042	3223	1362	2111	2951
Yield (seed)	kg ha^{-1}	3264	4306	4444	3609	4563	4835	2043	3167	4427
Lint-N	% (w/w)	0.18	0.17	0.22	---	---	---	---	---	---
Seed-N	% (w/w)	2.85	3.23	3.96	3.25	3.99	4.09	3.25	3.80	3.97
Above-ground biomass	kg DM ha^{-1}	6266	7556	9077	6685	5395	6042	4595	9622	7122
Above-ground biomass-N	% (w/w)	0.99	1.48	1.72	193	206	228	82	219	184
Fertilizer + application cost	AUD ha^{-1}	0	124.7	296.9	0	625	900	0	625	900
Gross Margin	AUD ha^{-1}	5629	7425	7663	5300	6075	6199	3000	4025	5600

GRAINS

Data for grains are quoted from a long-term (≈20 years) fertilizer trial located in western Victoria (after Norton, 2017) (Table 3). Further information can be retrieved from the GRDC Online Farm Trials database (https://www.farmtrials.com.au/), which provides open and free access to on-farm cropping research and fertilizer trials data. The NUE indicators presented in Table 3 reflect production (PFP_N, A_E) and recovery (PNB, A_R) efficiencies, respectively. For PNB and A_R, values around 1 in the long-term suggest that both N losses and mining of soil N are minimized as the amount of N removed from the system or in the harvested products is approximately equal to that applied as fertilizer. Values well below or well over 1 indicate surplus or deficit of N applied as fertilizer, respectively, and suggest that use-efficiency can be improved accordingly (Fixen et al., 2015; Norton, 2017). In general, values around 0.8 or higher can be achieved with best management practices (Ladha et al., 2005).

Table 3: NUE values estimated from wheat yield-to-nitrogen (N) responses reported by Norton (2017) from a long-term fertilizer trial conducted in western VIC under rainfed conditions. PFP_N: Partial factor productivity of applied N, A_E: agronomic efficiency, PNB: partial N balance, A_R: apparent recovery. Norton (2017) used an average price of grain of AUD300 per ton and an average fertilizer cost of AUD1 per kg N to estimate the net economic return.

Fertilizer rate, kg N ha^{-1}	Mean yield	PFP_N	A_E	PNB	A_R	Net economic return
Unit	**kg ha^{-1}**	**kg kg^{-1}**	**kg kg^{-1}**	**kg kg^{-1}**	**kg kg^{-1}**	**AUD ha^{-1}**
0	1900	---	---	1.36	0.54	---
20	2290	141	22	1.04	0.47	97
40	2220	71	11	0.74	0.37	56
80	2310	38	8	0.42	0.19	53
160	2320	18	3	<0.2	<0.1	-34

SUGAR

Data for sugarcane were sourced from experimental sites located in northern New South Wales (NSW) at Maclean (Rust, 2019, *pers. comm.*) and north Queensland (QLD) at Ingham (Wang, 2019, *pers. comm.*) (Table 4). The NSW ratoon crop was grown during the 2018-2019 season, while the QLD crop was grown during the 2017-2018 season.

Table 4: Data collated for sugarcane from northern NSW (Rust, 2019, *pers. comm.*) and QLD (Wang, 2019, *pers. comm.*). 'Query' refers to data requested from MPfN Project Leaders. Fertilizer + application cost is the cost of urea applied in subsurface bands, and gross margin is the difference between gross income and fertilizer cost for the year of harvest. (---) means data not provided, and DM and FW are dry matter and fresh weight, respectively. Both crops were grown for 12 months.

Location	---	Northern NSW			QLD		
Query	**Unit**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**
Fertilizer rate	kg N ha^{-1}	0	100	300	0	108	145
Millable cane	tonnes DM ha^{-1}	10.9	14.4	18.0	10.3	21.4	22.2
Millable cane	tonnes FW ha^{-1}	39.8	54.10	68.8	34.3	71.3	74.0
Millable cane-N	% (w/w)	0.22	0.23	0.38	0.175	0.168	0.178
Above-ground trash	tonnes DM ha^{-1}	6.01	7.81	8.92	3.70	6.01	7.16
Above-ground trash-N	% (w/w)	0.53	0.69	0.78	0.488	0.493	0.513
Fertilizer + application cost	AUD ha^{-1}	---	---	---	---	---	---
Gross Margin	AUD ha^{-1}	---	---	---	---	---	---

DAIRY

Data for dairy systems were provided by the MPfN Dairy team from three experimental sites located in northern and central NSW, and Victoria (VIC), respectively (Table 5).

Table 5: Data collected for pasture-based dairy systems in northern and central NSW (Rowlings, 2019, *pers. comm.*), and VIC (Belyaeva, 2019, *pers. comm.*), respectively. 'Query' refers to data requested from MPfN Project Leaders. Fertilizer + application cost is the cost of urea applied on the surface (broadcast), and gross margin is the difference between gross income and fertilizer cost. The cropping season for pasture-based systems is 12 months. (---) means data not provided, (*) assuming AUD1.30 per kg N spread, (**) AUD0.25 per kg DM, (†) AUD1.3 per kg N spread, (††) 1 kg DM ryegrass produces 1.2 L milk and milk is AUD0.5 L^{-1}.

Location	---	Northern NSW			Central NSW			VIC		
Query	**Unit**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**
Fertilizer rate	kg N ha^{-1}	0	410	495	0	120	240	0	240	480
Harvested biomass	kg DM ha^{-1}	7180	12650	14010	1481	5129	7493	4960	10610	13020
Harvested biomass-N	% (w/w)	2.89	3.31	3.53	1.80	2.10	2.50	2.68	3.10	3.51
Unharvested biomass	kg DM ha^{-1}	800	790	860	3	3	3	---	---	---
Unharvested biomass	% (w/w)	0.60	0.67	0.65	1.00	1.00	1.00	---	---	---
Fertilizer + application cost	AUD ha^{-1}	0	533*	644*	0	156†	312†	---	---	---
Gross Margin	AUD ha^{-1}		3162**	3502**	889††	3077††	4496††	---	---	---

HORTICULTURE

Two fruit tree cropping systems comprise the horticulture component of the MPfN Program. Data have been collected for mango plantations in the Northern Territory and cherry orchards in Tasmania (Table 6). These perennial cropping systems raise special issues with respect to partitioning annual fertilizer N applications into receiving plant biomass. While labelled N experiments allow the destination of the applied N to be measured, using an N budget approach assumes that the sink of that applied N in the crop is solely the annual prunings and annual litter without sequestration into pre-existing crop biomass. Studies with ^{15}N are being undertaken on both crops, but for the purposes of this report, applied fertilizer N recovered in the crop is assumed to be solely in the harvested fruit, and annual prunings and litter.

Table 6: Data collated for mango (Tilbrook, 2019, *pers. comm.*) and cherry (Quin, 2019, *pers. comm.*). 'Query' refers to data requested from MPfN Project Leaders. For mango, ammonium sulphate was applied in the drip line with a planting density of 250 trees per ha, while for cherry, calcium nitrate was applied in the drip line with a planting density of 1,333 trees per ha. The cropping season for mango and cherry is considered to be 12 months. Gross margin is the difference between gross income and fertilizer cost for the year of harvest. (---) means data not provided, and DM and FW are dry matter and fresh weight, respectively.

Location	---	Mango, Northern Territory			Cherry, Tasmania		
Query	**Unit**	**Nil N**	**Rate 1**	**Rate 2**	**Nil N**	**Rate 1**	**Rate 2**
Fertilizer rate	kg N ha^{-1}	0	12.5	25	0	90	---
Ungraded fruit	tons DM ha^{-1}	3.5	3.3	3.5	4.78	5.25	---
Ungraded fruit	tons FW ha^{-1}	19.4	18.6	19.6	25.70	28.25	---
Ungraded fruit-N	% (w/w), DM	0.59	0.59	0.67	0.66	0.78	---
Ungraded fruit-N	% (w/w), FW	0.084	0.093	0.086	0.12	0.15	---
Unharvested biomass (annual pruning)	tons DM ha^{-1}	1.1	---	---	2.68	3.52	---
Unharvested biomass (annual litter)	tons DM ha^{-1}	1.8	---	---	1.21	1.36	---
Unharvested biomass (annual pruning)-N	% (w/w), dry basis	0.60	---	---	1.03	1.45	---
Unharvested biomass (annual litter)-N	% (w/w), dry basis	0.71	---	---	1.19	1.30	---
Fertilizer + application cost	AUD ha^{-1}	0	45	55	0	104.04	---
Gross Margin	AUD ha^{-1}	12790	12325	12966	136497	150000	---

OBJECTIVE 3: IDENTIFY A SUITE OF NITROGEN USE EFFICIENCY INDICATORS THAT ARE RELEVANT TO COMMUNICATE CROSS-SECTOR RESEARCH FINDINGS FROM THE MPFN PROGRAM

PROPOSED NITROGEN USE EFFICIENCY INDICATORS

The following NUE indicators (Equations 23-27) may be adopted by the industries to consistently record and report NUE-related research in Australian agricultural systems.

$$NU_tE = \frac{TB}{U} \quad (23)$$

where: *NUtE* is fertilizer N utilization efficiency (kg kg^{-1}), *TB* is increase in total above-ground biomass (kg ha^{-1}) and *U* is increase in crop N uptake (kg ha^{-1}) due to fertilizer N application.

$$NU_PE = \frac{U}{N_R} \quad (24)$$

where: NU_PE is fertilizer N uptake efficiency (kg kg^{-1}), *U* is crop N uptake (kg ha^{-1}) of fertilizer origin, and N_R is fertilizer N application rate (kg ha^{-1}),

$$AE = NU_tE \times NU_PE \times HI \quad (25a)$$

where: *HI* is harvest index; therefore:

$$AE = \frac{TB}{U} \times \frac{U}{N_R} \times \frac{Y}{TB} \quad (25b)$$

By cancelling out the same terms, Equation (25b) yields:

$$AE = \frac{Y}{N_R} \quad (25c)$$

where: AE is agronomic efficiency of applied fertilizer N (kg kg^{-1}), Y is yield increase (kg ha^{-1}) due to fertilizer N application rate, and N_R, and

$$MR_F = \frac{Economic\ return}{N_R} \quad (27)$$

where: MR_F is the marginal return on applied fertilizer N (AUD kg^{-1} N).

When Equations 23-25 are applied to horticultural crops, units may be expressed as 'kg per tree' instead of kg per ha. Figure 2 illustrates the proposed suite of NUE indicators.

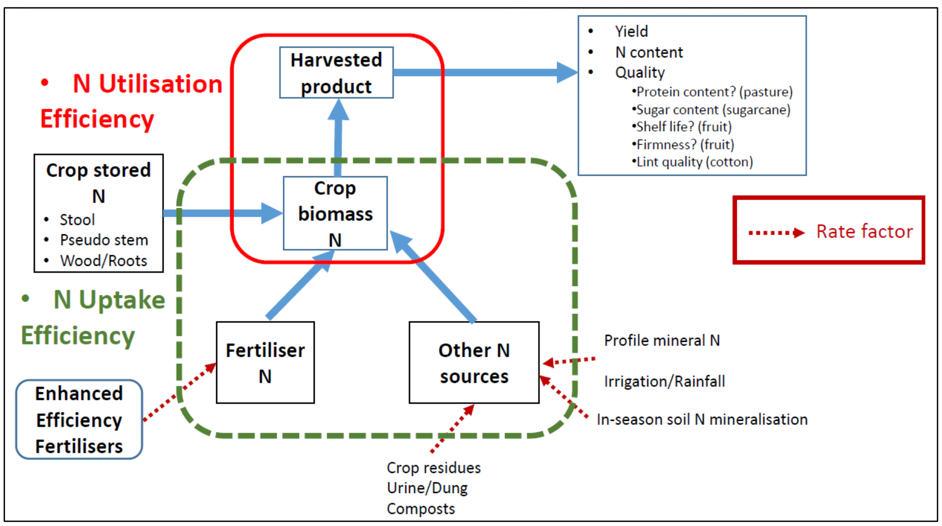

Figure 2: Conceptual diagram illustrating the suite of nitrogen (N) use efficiency (NUE) indicators that may be adopted by the industries to record and communicate NUE-related research in Australian agricultural systems.

A comparison of the proposed NUE indicators is shown in Table 7; this table highlights their relative cross-industry usefulness and the focus of individual metrics based on the primary factors that affect such metric. Both NU_PE and MR_F can be calculated as averages for the whole N response curve ($AverageNU_PE$, $AverageMR_F$) or for an increment of fertilizer N addition ($MarginalNU_PE$, $MarginalMR_F$) (Figure 3), and as maximum yield is approached, the marginal values of these two indicators decrease. A cross-industry comparison of NUE is presented in Table 8 based on data sourced from the MPfN Program and using the proposed suite of NUE indicators defined in Equations 23-27.

Table 7: Comparison of proposed NUE indicators for Australian agricultural systems. (†) Modified from Fixen et al. (2015).

Proposed NUE indicator	Acronym	Focus	Factors affecting	(†) Interpretation	Cross-industry usefulness
Fertilizer N utilization efficiency	NU_tE	Productivity	Environmental constraints to crop production; varietal/cultivar differences; general crop and soil husbandry.	Crop's ability to transform N taken-up from all sources into total biomass.	Limited.
Fertilizer N uptake efficiency	NU_PE	Productivity, Environmental	Off-site N losses.	Uptake per unit of N applied. If calculated by the difference method, proportion of N applied taken-up by the crop.	Benchmarks cropping system NUE in terms of fertilizer N recovery.
Agronomic efficiency of applied fertilizer N	AE	Productivity, Environmental	Environmental constraints to crop production; varietal/cultivar differences; general crop and soil husbandry; off-site N losses.	Productivity per unit of N applied. If calculated by the difference method, then this shows net productivity per unit of N.	Benchmarks cropping system NUE in terms of harvested product produced per unit of fertilizer N applied.
Marginal return on applied fertilizer N	MR_F	Profitability	Relativity of fertilizer cost to product value (price ratio).	Economic return per unit of N applied	Benchmarks cropping system NUE in terms of harvested product economic return per unit fertilizer N applied.

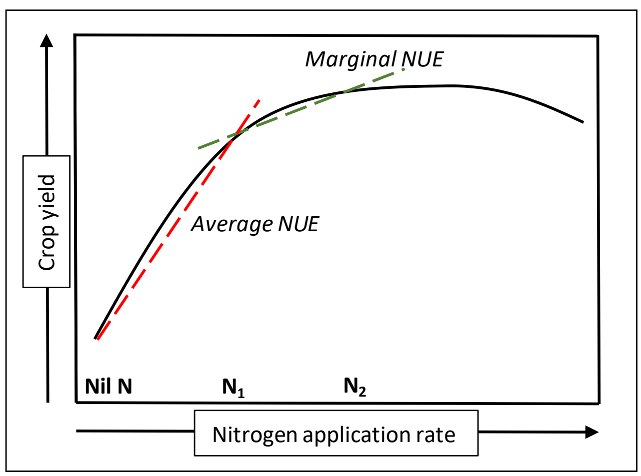

Figure 3: Conceptual diagram illustrating the derivation of 'average' and 'marginal' nitrogen (N) use efficiency (NUE) indicators; N_1 and N_2 are incremental N application rates.

Table 8: Cross-industry comparison of NUE based on data sourced from the MPfN Program and using the proposed suite of NUE indicators defined in Equations 23-27. (*) No crop biomass measured for this crop, (†) requires checking, CN is calcium nitrate (15.5% N), ammonium sulphate (21% N, 24% S), urea (46% N), $ is AUD.

Crop, location	Cropping season	N_R	Fertilizer type, placement	NU_tE	Average NU_PE	Marginal NU_PE	AE	Average MR_F	Marginal MR_F	HI (DM)	HI (N)	Nil N crop uptake
Unit	**Month**	**kg N ha^{-1}**	**---**	**kg kg^{-1}**	**kg kg^{-1}**	**kg kg^{-1}**	**kg kg^{-1}**	**$ kg^{-1}**	**$ kg^{-1}**	**---**	**---**	**kg ha^{-1}**
Sugarcane, QLD	12	0, 108, 145	Urea, subsurface band	385	0.28	0.29	82.1	11.52	0.79	0.76	0.52	36
*Sugarcane, NSW	12	0, 100, 300	Urea, subsurface band	N/A	N/A	N/A	76.7	10.53	9.44	N/A	N/A	N/A
Cotton, QLD	6	0, 125, 180	Urea, subsurface band	46	0.46	0.30	11	5	2.25	0.57	0.67	193
Cotton, NSW	6	0, 112, 292	Urea, subsurface band	50.7	0.62	0.46	17.06	7.96	1.61	0.47	0.54	160
Dairy, NNSW	12	0, 410, 495	Urea, broadcast	29.7	0.60	0.90	28.3	5.44	3.08	0.94	0.99	212
Dairy, Central NSW	12	0, 120, 240	Urea, broadcast	40	0.78	0.66	25.1	11.56	11.82	0.99	0.99	27†
Dairy, VIC	12	0, 240, 480	Urea, broadcast	24.9	0.67	0.53	16.8	N/A	N/A	N/A	N/A	133
Mango, NT	12	0, 12.5, 25	Ammonium sulphate, drip	161.8	0.02	-0.04	8	3.2	N/A	0.53	0.51	40
Cherry, TAS	12	0, 90	CN, drip	92.2	0.11	N/A	28.3	129.8	N/A	0.52	0.37	74

The NUE indicator framework developed by the EU Nitrogen Expert Panel (2015) was adapted for the Australian cotton industry (Figure 4) based on data from earlier studies (Rochester, 2011, 2012; Smith et al., 2014; Antille, 2018; Macdonald et al., 2018). This framework was also proposed by De Klein et al. (2017) for dairy production systems. The slope of the green diagonal lines represents the target NUE range. This NUE target range, expressed as partial factor productivity of applied N (PFP_N), is derived from Rochester's (2011, 2012) maximum value range of optimum NUE (18 kg lint kg^{-1} N) and 50% of that value (9 kg lint kg^{-1} N), which is used to establish the minimum NUE for cotton production systems. This percentage value (50% of the maximum NUE) is suggested as a reference for cotton based on earlier work (e.g., EU Nitrogen Expert Panel, 2015; De Klein et al., 2017) conducted for other industries. The diagonal dashed line represents the minimum value range of optimum NUE determined by Rochester (2011, 2012) and equates to 13 kg lint kg^{-1} N when NUE is expressed as PFP_N. The red horizontal dashed line denotes the desired minimum level of productivity for irrigated cotton (equally the N output associated with such productivity level). The blue diagonal line represents a limit related to maximum N surplus to avoid significant environmental losses of N. The proposed criteria are used to identify the most desirable range of outcomes, which is represented by the area limited by the red horizontal dashed line, the blue diagonal line and the maximum NUE line, respectively. The area between the blue diagonal line and the minimum NUE line shows that while NUE is within the 'acceptable' target range, measures should be taken to further improve NUE. These measures include approaches to fertilizer best management practices such as the '4R' (right product, right rate, right place, and right time) Nutrient Stewardship (Roberts, 2007), and joint management of water and the soil physical environment. The shaded yellow areas denote NUE too high (above maximum NUE line) or NUE too low (below minimum NUE line) where there is an increased risk of mining of soil N or an increased risk of N loss to the environment when N application rate is not optimized for the cotton system.

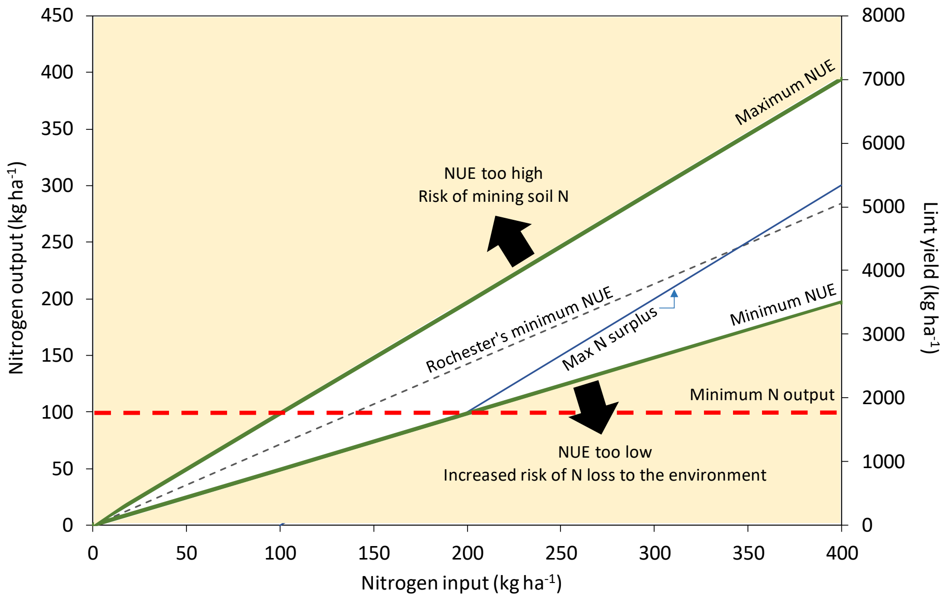

Figure 4: Conceptual diagram of the nitrogen use efficiency (NUE) indicator framework developed by the EU Nitrogen Expert Panel (2015), used by De Klein et al. (2017) for dairy production systems, and adapted here for the Australian cotton industry based on data reported in earlier studies (Rochester, 2011, 2012; Smith et al., 2014; Antille, 2018; Macdonald et al., 2018).

OBSERVATIONS FROM CROSS-INDUSTRY DATA

RECOVERY OF FERTILIZER N AS ESTIMATED BY NU_PE

With the exception of the horticultural tree crops, average NU_PE indicates that across the agricultural systems, the recovery of fertilizer N ranged from 28% (sugarcane) to 78% (dairy) (Table 8). In an extensive review of NU_PE values published in the international literature, Ladha et al. (2005) reported a median value of 55% for grain crops (primarily rice, wheat and maize) in the year of application, although different crops had different median values (*viz*. maize: 65±3%; wheat: 57±2%; rice: 46±1%). For a particular cropping system, NU_PE varies with season and fertilizer form, as shown in Bell et al. (2014) for sugarcane. Therefore, while it is not possible to make definitive comparisons across the MPfN agricultural systems, the low values for the sugarcane and QLD cotton cropping systems (Table 7) indicate that there is potential to improve N fertilizer recovery in these systems by mitigating N loss pathways via changed practices such as rate, form, placement and timing of N application; in both cropping systems, the efficacy of enhanced efficiency fertilizers (e.g., fertilizers with nitrification inhibitors; urease inhibitors, and controlled release coated fertilizers) is currently being assessed. More significant increases in NUE often result from increasing yields than from reducing N rates (Fixen and West, 2002). However, NUE could be improved a little by reducing N use in situations where fertilizer N applied and yield are not well correlated, as shown for cotton by Smith et al. (2014).
It is also suggested that the very low NU_PE of the mango and cherry systems is a consequence of the difficulty involved in partitioning the comparatively low N application rates across the crop biomass.

CONTRIBUTION TO CROP N UPTAKE FROM SOIL PROFILE N AND IN-SEASON SOIL N MINERALISATION

Table 8 shows that initial soil profile mineral N plus in-season soil N mineralisation contributed from 36 kg N ha^{-1} (sugarcane) to 212 kg N ha^{-1} (dairy pasture), with the contribution to cotton being much higher than for sugarcane or the horticultural tree crops. This source of N needs to be properly accounted for in the N budget approach to calculating N fertilizer requirements and highlights the need for a decision support tool (DST) to estimate in-season soil N mineralisation. This DST would need to take account of the soil's N mineralisation potential and the seasonal outlook (to account for soil temperature and soil water content effects on nitrification) as has been proposed by Orton et al. (2019). The DST would need to have a known level of certainty to provide the end user with confidence in its application.

ECONOMIC RETURN FROM APPLIED N FERTILIZER

When expressed as average marginal return, there is a wide variation across industries with values ranging from AUD3.20 kg^{-1} N (mango) to AUD129 kg^{-1} N (cherry) (Table 8). While much of this variation is due to the necessarily different assumptions being made about the value of the harvested product by each industry, the fact remains that all average marginal returns and most marginal MR_F are above the nominal cost of about AUD1.50 per kg N applied as urea.

Therefore, the current 'optimum rates' (as nominally assigned to the N2 rate data in this paper) of the MPfN projects may not have reached point 'C' in Figure 1 indicating there is no economic driver to reduce N rates below the N2 rate of the various agricultural systems.

FUTURE RESEARCH REQUIREMENTS

The following research priorities were identified for each of the industries in the MPfN Program:

(1) Benchmark the effects of various N fertilizer management practices (form, timing, rate, placement) on NU_PE to inform best management practices;

(2) Develop and promote user-friendly decision support tools for estimating the magnitude of in-season soil N mineralization to crop N requirements;

(3) Undertake a consistent economic analysis of the marginal returns from applied N across all industries. If it is shown that the marginal return from undertaking N management practices to improve industry NUE is negative, then incentive schemes need to be considered to ensure the primary producer is not financially disadvantaged. Nutrient trading/credit schemes and premium payments for producing environmentally certified products are two possible strategies to achieve this outcome,

(4) While common NUE definitions relevant to the MPfN Program were proposed, future examination of industries' NUEs should be undertaken to verify and expand the initial observations conducted as part of this project. The usefulness and robustness of the proposed NUE metrics could be improved by progressively incorporating data produced by the program. Thus, a recommendation is to undertake a retrospect meta-analysis of MPfN NUE to consolidate such data, re-assess NUE indicators, and inform NUE research.

(5) An NUE indicator framework was adapted for the Australian cotton industry (Figure 4) based on a framework previously developed by the EU Nitrogen Expert Panel (2015). A recommendation is made to apply this concept to other industries as data from the MPfN Program is released.

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Part 4 – Final Report Executive Summary

This work was undertaken to assist with reporting the MPfN Program's outputs and outcomes across industry sectors. Collation and review of nitrogen (N) use efficiency (NUE) indicators used in Australia and internationally, as compiled in this report, will contribute to that effect. The following NUE indicators are proposed; namely: (1) fertilizer N utilization efficiency (*NUtE*), (2) fertilizer N uptake efficiency (NU_PE), (3) agronomic efficiency of applied fertilizer N (*AE*), and (4) marginal return on applied fertilizer N (MR_F). Collectively, these NUE indicators reflect productivity, environmental, and profitability aspects of fertilizer management. Application of the proposed NUE indicators to the focus agricultural systems of the MPfN Program will enable NUE data to be reported in a standardized manner. The calculation, interpretation, and cross-industry usefulness of these NUE indicators is presented and discussed. Worked examples are also provided based on data derived from the MPfN Projects.