More profit from nitrogen: enhancing the nutrient use efficiency of intensive cropping and pasture systems.

Project Number: RnD4Profit-15-02-021

Final Evaluation and Economic Case Studies Consultancy Terms of Reference (ToR)

December 2019

(Closing date: February 21st 2020)
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    Nitrogen Use Efficiency Indicators for the Australian Cotton, Grains, Sugar, Dairy and Horticulture Industries, Diogenes L. Antille & Philip W. Moody. ............................ 15
1. Background

The More Profit from Nitrogen: Enhancing the Nutrient Use Efficiency of Intensive Cropping and Pasture Systems Project (MPfN) is a cross-sectoral collaboration led by the Cotton Research and Development Corporation (CRDC) and funded through the Australian Government Department of Agriculture’s (DoA) Rural Research and Development for Profit program (Rural R&D for Profit). It is a partnership comprised of Australia’s four major intensive users of nitrogenous fertilisers: cotton, dairy, sugar and horticulture. The program partners are CRDC, Dairy Australia (DA), Sugar Research Australia Ltd (SRA), Hort Innovation Australia Ltd (Hort Innovation), NSW Department of Primary Industries, NT Department of Primary Industry and Resources, Queensland University of Technology, University of Southern Queensland- Centre for Engineering in Agriculture, The University of Melbourne, University of Tasmania- Tasmanian Institute of Agriculture, University of Queensland, Queensland’s Department of Agriculture and Fisheries and Department of Environment and Science.

The objective of Rural R&D for Profit is to realise productivity and profitability improvements for primary producers, through:

a) generating knowledge, technologies, products or processes that benefit primary producers;

b) by strengthening pathways to extend the results of rural R&D, including understanding the barriers to adoption; and

c) establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture.

MPfN was established with an aim to bring about increased farm profitability and reduced environmental impact by increasing nitrogen use efficiency (NUE) across the four industry sectors, measured by a reduction in the amount of applied nitrogen (N) required to produce each unit of product. This was to be delivered by better matching N application source (including Enhanced Efficiency Fertilisers (EEFs)), timing and rate to crop/ pasture demand through improved understanding of overall N budget contributions and losses, and the interacting soil, water, climatic and management practice factors that influence these.

Under the umbrella of MPfN, 10 sub-projects, consisting of a mix of field, laboratory and modelling based studies were established, led by the following research organisations (refer Attachment 2, Table 2):

- NSW Department of Primary Industries (NSW DPI) x2 projects- Sugar & Cotton
- University of Southern Queensland – Centre for Engineering in Agriculture (USQ)- Cotton
- Queensland University of Technology (QUT)- Dairy
- University of Melbourne (UoM) x2 projects- Dairy
- Queensland Government- Department of Environment and Science (DES)- Sugar
- Queensland Government- Department of Agriculture and Fisheries (QDAF)- Sugar
- Northern Territory Government- Department of Primary Industry and Resources (NTDPIR)- Mangoes
- University of Tasmania- Tasmanian Institute of Agriculture (TIA)- Cherries

An additional small cross-program project was also contracted on May 2019 with CSIRO, in partnership with The University of Queensland, “More profit from Nitrogen - Nitrogen use efficiency indicators for the Australian cotton, sugar, dairy and horticulture industries”.

More can be found Here on the Program’s website or Here directly from the MPfN Booklet.
2. MPfN delivery

The Commonwealth Agreement committed MPfN to focus on three key areas of research, each with its own specific set of research activities:

1. To generate greater knowledge and understanding of the interplay of soil, weather, climatic and farm management factors to optimise nitrogen N formulation, rate and timing across industries, farming regions and irrigated/ non-irrigated situations (Activity B5 - Optimising NUE in irrigated systems);
2. To generate greater knowledge and understanding of the contribution (quantifying rate and timing) of mineralisation to a crop or pasture’s N budget (Activity B6 - Better understanding N supply through mineralisation); and
3. To generate greater knowledge and understanding of how enhanced efficiency fertiliser (EEF) formulations can better match a crop or pasture’s specific N requirements (Activity B4 - Extracting value from enhanced efficiency fertilisers).

Sub-research projects have been delivering outputs under one, two or all three of these activities.

MPfN is also delivering communication and extension activities aligned with key Rural R&D for Profit objectives:

1. To strengthen pathways to extend the results of the research to target audiences, including understanding potential barriers to adoption; and
2. To establish and foster industry and research collaborations on NUE to aid further innovation for Australian agriculture.

Cross-project collaboration has also been a focussed output of MPfN. As well as ongoing informal communication between projects, two key activities have formally delivered opportunities to exchange information and seek input:

(1) Annual More Profit from Nitrogen Partner Forum; and 
(2) Nitrogen Natters newsletter- a quarterly publication compiling research, communications and extension updates across the Program.

MPfN was originally four years in duration, commencing July 2016 until June 2020. However, due to delays in contracting and sub-contracting, a twelve month extension was granted by the DoA for a final reporting date of September 30 2021. This variation has resulted in a staggered end date to the sub-research projects (refer Attachment 2, Table 2).

As a cross-sectoral, collaborative program, MPfN involves over 30 organisations who are contributing both cash and in-kind support as sector partners, research partners and project collaborators. By completion of the project, research and extension activities will have been undertaken across 50 geographically spread research sites, from Darwin in the north to Hobart in the south.

Strategic direction of MPfN is provided by the Program Management Committee (PMC) comprised of representatives from the research and development corporations (RDCs) and the eight lead research organisations. Representation from CRDC, DA, Hort Innovation, SRA, QDES and NTDPIR has changed over the project duration. A Science Coordinator was engaged to oversee project management of the MPfN Program in November 2016, with a key focus upon monitoring and evaluation (M&E), communications, reporting and cross-project/ partner collaboration. This position is contracted until September 2021. Attachment 2, Table 1 outlines the role of each stakeholder involved in the Program.
The MPfN M&E Plan (April 2017) outlines the framework and work plan which has been implemented to monitor, report and evaluate progressive and final outcomes of MPfN by the Science Coordinator, Project Manager (CRDC) and the PMC.

The ten research partners have been required to provide six-monthly reports to CRDC on Milestones within their CRDC Full Research Proposals (FRPs) and DoA KPI. The Science Coordinator is responsible for establishing and overseeing reporting processes to meet the requirements of CRDC, the three RDC partners and DoA. A single reporting template is used to satisfy obligatory requirements of all parties for the specified reporting period.

In order to manage the reporting timeframes required by DoA, CRDC established a reporting framework with the partners. Refer Attachment 2, Table 3.

3. MPfN mid-term evaluation report

In April 2019, Coutts J&R Pty Ltd was engaged by CRDC to undertake a qualitative mid-term project evaluation. The process of seeking input and feedback from the key stakeholder groups of research, industry, service providers and producers, was undertaken by telephone interview. A written questionnaire was also used to survey research team members. The overarching recommendations were to:

1. Continue the project management approach
2. Engage service providers more fully
3. Facilitate the development of relevant and effective messaging
4. Develop communications packages

A copy of this report can be found here: MPfN Program Mid-term Evaluation Report

4. Purpose of Tender

On behalf of the PMC, CRDC is undertaking the tender process to engage a suitably qualified consultant to deliver two outputs:

(1) The MPfN Final Evaluation Report (1)

Purpose: To evaluate the extent to which MPfN has delivered upon the objectives of the three key research activities and it’s potential to result in improved on-farm N management strategies that deliver increased NUE across the industries.

(2) Preparation of sub-research project Economic Case Studies (up to 10)

Purpose: To evaluate economic impact of adoption of new or improved practice recommendations resulting from the sub-research projects, i.e. how much “more profit” would a farm business make through adoption of the research compared to “business as usual” N management strategies.
5. Scope of the MPfN final evaluation (Output 1)

The final evaluation for MPfN is aimed at assessing the extent to which greater understanding and knowledge has been generated amongst the identified internal and external program stakeholders and the potential for this greater understanding and knowledge to improve NUE and on-farm profitability. The MPfN M&E Plan (April 2017) specified Performance Indicators within the Program Logic Framework (Section 2.4 of the plan) for each of these evaluation levels. These indicators were established for project-end evaluation purposes but were also considered during mid-term evaluation processes to gauge whether MPfN was on track to deliver project aims and objectives by June 2021 (refer to Attachment 1).

The evaluation consists of two components:

1. **Evaluate successful delivery of the project objectives:**
   - Conduct an independent qualitative assessment and review of final sub-research reports to gauge the extent to which increased “knowledge and understanding” was achieved to deliver new, updated or validated NUE practice management strategies to industry.
   - Assess whole-of-program activities and deliverables against the MPfN Project Management Plan (achievement of milestones, outputs, KPI within timeframes), MPfN Communication and Extension Plan (activities planned, prepared and delivered) and M&E Plan (governance, management, reporting).

2. **Evaluate immediate and legacy impact of the project upon industry nitrogen management practices to improve on-farm NUE:**
   - Conduct an independent qualitative assessment to gauge “effectiveness, ”extent” and “increased knowledge and understanding” across stakeholder groups.
   - Assess intent of industry to adopt and promote findings/ recommendations of the sub-research projects.

The evaluation will examine all five years of the MPfN. A targeted approach is proposed, where MPfN is evaluated for how well it met objectives and for efficiency and effectiveness of activity implementation. The evaluation processes will require collaboration and open dialogue between the Tenderer and the Science Coordinator.

**Evaluation Methodology**

The following are the key evaluation questions (KEQ) to be addressed by the external evaluation consultancy:

1. To what extent did the activities of MPfN contribute to increased understanding and knowledge of the factors which influence NUE across the four industries and (both at a research and service provider/ producer level)?
2. To what extent did the activities of the Program identify new or update/ validate existing NUE strategies/ technologies across the four industries and (both at a research and service provider/ producer level)?
3. To what extent are key stakeholders confident that the MPfN activities have/ will over time result in greater confidence to apply NUE strategies resulting in more consistent profit and reduced environmental impact gains for primary producers of the four industries?
4. What evidence is there (anecdotal & outputs) that the research activities have effectively demonstrated opportunities for each industry to improve NUE without production loss or increased production and profit?

5. To what extent are key stakeholders confident that the MPfN planning, monitoring and reporting instruments assisted to effectively deliver upon the research, communication and extension objectives of the program?

6. What, if any, unintended outcomes (positive or negative) resulted from the MPfN (whole-of-program, research and service provider/ producer levels)?

7. What changes in implementation/processes could have improved effectiveness and/or impact?

It is anticipated that the tenderer will engage with stakeholders evaluate:

1. Productivity and profitability:
   Increased knowledge and understanding of new NUE technologies and best management practices (BMPs) generated through the program.
   Benefits for primary producers in the context of:
   - The impact of research findings; and
   - The extent to which Program outcomes have potential to increase productivity and/or profitability of primary producer through increased NUE.

2. Efficiency and effectiveness:
   The role of identified Program activities and outcomes in increasing confidence and strengthening the pathway for extension and adoption of new/ adapted industry NUE BMPs, guidelines and technologies by end-users.
   The role of Program coordination, communication, monitoring and reporting activities in successfully providing a supportive framework for research to extension activities.

3. Collaboration:
   How collaboration and information exchange opportunities were valued by the project partners and whether these resulted in increased collaboration between research teams/ industry, changes to research methodology, formation of new beneficial collaborations and stimulation of new ideas for future innovation and research needs.

4. Extension and adoption:
   The success of field trials, local events and communications in engaging and providing local relevance to producers and service providers, resulting greater NUE understanding.
   MPfN influence upon increased end-user confidence to adopt new/ updated/ validated NUE practice management strategies.
6. Scope of the economic case studies (Output 2)

An important means by which to articulate the impact of MPfN research outcomes upon primary producer business profit is by using an economic analysis approach. The objectives of each of the research activities (Section 2) were established to address gaps in knowledge and understanding that constrained opportunity to improve NUE. By improving knowledge and understanding, sub-research projects will provide new and/or amended NUE strategy recommendations to industry. The economic case studies are to explore the likely economic implications for farmers of adopting these NUE strategies compared to current industry practice and/or the farmer case study “typical” practice.

This component of the project evaluates the question for each industry: *Will a primary producer generate more profit from N should they adopt the NUE strategy recommendations of research?*

What we know from progressive findings of the MPfN Program is that the potential to generate “more profit from nitrogen” may come from varying scenarios: total N application rates reduced without impact to production (cost savings), production gains from standard practice N inputs that are better timed with crop/ pasture uptake or availability of soil mineralised N sources (increased income), increased N application leading to greater production (increased profit margin), N inputs optimised regarding their impact on product quality (fruit colour/taste) (increased quality and thus income) or the use of more costly EEF under certain climatic/ seasonality conditions to reduce the risk of N depletion and therefore production losses, to highlight only a few of the possible scenarios.

Across industries, the pathway to improved profitability and the economic metric used will vary dependent upon the industry measure of the biomass produced and/or market economic expression.

The expected Economic Case Studies output:

- Up to 10 case studies (minimum of two per industry) developed using a consistent communication approach (key headings, terminology, graphs & figure layout) of no more than four pages each.
- Target audience to be considered in preparation of the documents is an advisor/ producer level.
- Final documents in Microsoft Word and Pdf.

Economic Case Study Methodology

The following are seen as the key steps to be taken in preparation of the economic case studies:

- Review and consider the NUE and economic indicators as recommended in the MPfN Program report, *Nitrogen Use Efficiency Indicators for the Australian Cotton, Grains, Sugar, Dairy and Horticulture Industries* by Diogenes L. Antille & Philip W. Moody (Attachment 3).
- Review and consider the recommendations of the draft/ final report of each sub-research project and liaise with project leaders to determine the NUE strategies to be economically assessed and the appropriate data-sets from the research to be used.
- Consult with project leaders, RDC representatives and, where possible, industry extension leads, on the economic metrics that have relevance and will work best for communication to the broader industry. As a part of this step, review existing industry resources (if available) that discuss the economic implications of N strategy.
- Reach agreement with each industry upon the farming scenario, ‘typical’ NUE strategies and economic metrics to be used in preparation of the case studies for that industry.
7. Confidentiality, Conflict of Interest and Privacy

The successful tenderer will be required to sign a confidentiality agreement with CRDC and must keep confidential all information, documents, data and software that is provided by CRDC or its research partners or collected by the consultant for the purpose of undertaking the evaluation activities.

All data collected will be owned by CRDC and a copy must be provided to CRDC. After completion of the consultancy the consultant must delete all survey data and in particular all personal information collected. The consultant must comply with the Australian Privacy Principles under the Privacy Act 1988.

Each tender will be required to include any actual or potential conflicts of interest. If the tender is successful, you will be required to advise CRDC in writing of any changes in conflicts of interest at the time of contracting the services with CRDC or at any time during the term of this agreement should a conflict or potential conflict arise. The CRDC Annual Report lists CRDC’s stakeholders, directors, staff and research partners and may be helpful in determining if you have a conflict of interest. The CRDC Annual Report is available at http://www.crdc.com.au/about-Us under the Corporate Publications page.

8. Two-staged delivery of consultancy

The activities and deliverables of the tender are divided into two distinct activity periods to reflect the progressive final reporting dates of sub-research projects of MPfN.

The project is expected to commence in March 2020, with the final evaluation report and all case studies to be completed by 11 June 2021.

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Deliverable</th>
<th>Due date</th>
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<tbody>
<tr>
<td><strong>STAGE ONE</strong></td>
<td></td>
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<tr>
<td>Milestone 1</td>
<td>Start-up meeting (teleconference) with Science Coordinator and CRDC R&amp;D Manager</td>
<td>30 March 2020</td>
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</table>
| Milestone 2 | Detailed project plan to undertake both Stage 1 & 2 to CRDC for approval (in collaboration with the Science Coordinator):  
- Project methodology (Evaluation & Case Studies);  
- Identify stakeholders to be consulted (Split Stage 1/ Stage 2);  
- Evaluation survey/interview questions & guide. Privacy statement for the surveys to note CRDC as the owner of the data, why the data is being collected, and what purpose(s) it will be used.  
- Outline of economic metrics to be used for each industry (upon review of industry materials), data collection processes with project leaders and provide copy of standard case study template to be used. | 13 April 2020 |
| Milestone 3 | Complete interview / survey process (evaluation)- RRDP1713, RRDP1714, RRDP1715, RRDP1717 & RRDP1718. | 22 May 2020 |
| Milestone 4 | Completed Case Studies for above sub-research projects (reviewed & approved by Science Coordinator/project leaders/ industry RDCs) | 30 June 2020 |
| | Draft evaluation report – approved layout and content to date | 30 June 2020 |
| **STAGE TWO** | | |
| Milestone 5 | Recommencement meeting (teleconference) with Science Coordinator and CRDC R&D Manager | 26 February 2021 |
| Milestone 6 | Update of project plan (based upon previous year feedback) to undertake Stage 2 to CRDC for approval. | 12 March 2021 |
| Milestone 7 | Complete interview / survey process (evaluation)- RRDP1712, RRDP1713, RRDP1714, RRDP1715, RRDP1717 & RRDP1718. | 30 April 2021 |
Milestone 8

<table>
<thead>
<tr>
<th>RRDP1716, RRDP1719, RRDP1720 &amp; RRDP1721.</th>
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<tbody>
<tr>
<td>Completed Case Studies for above sub-research projects (reviewed &amp; approved by project leaders/ industry RDCs)</td>
</tr>
<tr>
<td>Final sections of the evaluation report and summary approved by CRDC &amp; Science Coordinator. Survey data provided to CRDC.</td>
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</table>

The draft and final report must include:

- Executive summary of findings
- A report on identified stakeholders and consultation activities undertaken
- Evaluation findings presented to address key evaluation questions, referencing extent to which the M&E Performance Indicators have been delivered:
  - Collation/ summary of the core themes using a thematic analysis template supplied by CRDC
  - Analysis on program effectiveness and outcomes presented as discussion and figures
  - Interviewee quotes (Anonymously reported)
- Key messages for each industry emanating from the research of MPfN and significance of the step-change delivered for each industry by MPfN.
- Recommendations for industry and agencies with regards to:
  - Adoption of the research
  - Gaps in knowledge, understanding and/or further validation of the research for industry regions/ systems.
  - Further collaboration

9. Consultation

A number of stakeholders will be consulted during the evaluation, including RDCs, research partners, industry groups and end users of research, to be determined in consultation with the Science Coordinator and specified in the project plan.

The Project Leaders of each sub-research project with be the key conduit for presenting the outcomes of their research as economic case studies that will demonstrate drivers for adoption of recommended technologies, strategies and management practices.

It is expected that the consultant will interact regularly with the MPfN Science Coordinator and seek clarification/ confirmation whenever required.

10. Expressions of Interest (EOI)

Expressions of interest are now sought by suitably qualified and experienced evaluation consultants to undertake this body of work.

**Selection Criteria**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weighting (%)</th>
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<tbody>
<tr>
<td>1. A sound understanding of the nature and importance of NUE to the Australian cotton, sugar, dairy and horticulture industries</td>
<td>20%</td>
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<tr>
<td>2. Soundness and clarity of the proposed methods to seek answers on the KEQ and prepare the evaluation report in accordance with the specified deliverables</td>
<td>40%</td>
</tr>
<tr>
<td>o The applicant must describe how the methodology employed will enable the project outcomes to be delivered. Different options may be</td>
<td></td>
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presented. Staged milestones/outputs should be clear.

| 3. | Soundness and clarity of the proposed methods to use a relevant industry approach to economic assessment, present economic evaluation using sub-research project findings and prepare case studies in accordance with the specified deliverables.  
|    |   o The applicant must describe how the methodology employed will enable the project outcomes to be delivered. Different options may be presented. Staged milestones/outputs should be clear. |

| 4. | Demonstrated capacity of the nominated team to provide project implementation for the timely delivery of high quality outputs:  
|    | o The applicant must describe the research team’s project skills and experience and may include a recent example of a completed project (s). |

| 5. | The cost effectiveness of this project  
|    | o The research applicant should demonstrate market value and market fairness for the proposed budget. The budget should be detailed enough to understand components of work and milestones. Three to four Milestones would be sufficient. The budget should be (Ex GST). |

## Further Information
Marguerite White, More Profit from Nitrogen Program Science Coordinator for CRDC, 0447 500 415 or mwhite@icdprojectservices.com.au.

## Submissions
All EOI must be received by 5pm, February 21st 2020 via email to grants@crdc.com.au.
Intermediate Outcomes

**Achievable within the life of the project - What will result from the project activities?**

**Activity B4** - A greater knowledge and understanding of how enhanced efficiency fertiliser (EEF) formulations can better match a crop or pasture’s specific N requirements.

**Extent to which** there is greater knowledge/understanding of EEF products/ blends which result in increased NUE under a range of soil, climatic and system conditions across the four sectors.

**Extent to which** knowledge/understanding of the profitability and production benefits of EEF product/blend use has been determined and extended across the four sectors.

**Extent to which** research has demonstrated increased knowledge/understanding of how EEF use can reduce N loss from the farm system without impact to product yield or quality.

**Extent to which** the potential for new EEF formulations and combinations of existing EEFs to better match nitrogen crop demand has been determined.

**Extent to which** the research demonstrates future potential for new EEF technology to reduce N loss from the farm system through simulation and modelling techniques.

**Activity B5** - A greater knowledge and understanding of the interplay of factors to optimise nitrogen (N) formulation, rate and timing across industries, farming regions and irrigated/non-irrigated situations

**Extent to which** knowledge/understanding of total losses of N from certain farming systems has increased.

**Extent to which** significant N loss pathways are understood and have resulted in targeted recommendations for improved management of NUE on irrigated farms.

**Extent to which** profitability and production outcome knowledge/understanding has increased on adopting identified practice modifications in N and irrigation management across the four sectors.

**Extent to which** research has resulted in changed BMP recommendations or the preparation of new guidelines/benchmarks for industry.

**Extent to which** likely impacts upon profitability, production and the environment are understood and have been demonstrated to industry through research outputs.

**Activity B6** - A greater knowledge and understanding of the contribution (quantifying rate and timing) of mineralisation to a crop or pasture’s nitrogen budget

**Extent to which** the effectiveness of MIR/NIR has been explored against other methods to predict soil mineralisable N.

**Extent to which** developed tools/resources provide increased knowledge/understanding for producers (and services providers) to make more informed decisions in source, rate, timing and placement of N fertiliser.

Program Activities

**Research and stakeholder engagement outputs - What will the project deliver?**

**Extent to which** the six research projects of Activity B4 deliver upon contracted Outputs: Sugar 4(a) to 4 (h), Horticulture 4 (j) to 4 (l) & Dairy 4 (m).

**Extent to which** the seven research projects of Activity B5 deliver upon contracted Outputs: Cotton 5(a) to 5 (b), Horticulture 5 (c) to 5 (f) & Dairy 5 (g) to 5 (k).

**Extent to which** the seven research projects of Activity B6 deliver upon contracted Outputs: Cotton 6(a) to 6 (b), Horticulture 6 (c) to 6 (d), Sugar 6 (e) to 6 (h) & Dairy 6 (i) to 6 (m).

**Extent to which** field trials provide a certain level of relevance to local producers and service providers resulting in ongoing engagement during project duration and generation of greater NUE understanding.

**Extent to which** producers and service providers are increasing their knowledge on N dynamics under varying climatic/management conditions and understand what this means to their farm business.

**Evidence** that opportunities are provided for planned cross sector collaboration on methodology approaches, shared information on progressive and final findings as well as key learnings. These opportunities are resulting in greater knowledge and understanding amongst the research partners/collaborators.

**Documented** outcomes of both formal and informal collaborations taken place between research partners, project collaborators and further external stakeholders as a result of MPfN Program activities.

**The details of partner forums** (location, topics, process), extent of representation of targeted stakeholders, stakeholder reactions, input received and actions taken as a result.

**Mid-term evaluation report**

**Evidence that** the MPfN Program is progressing towards greater knowledge and understanding in relation to
the three intermediate Outcomes:

- What knowledge and understanding gains have been made at this point?
- What have been the enabling activities to stimulate greater knowledge and understanding?
- Are there signs that greater knowledge and understanding will lead to adoption of future recommendations?
- What are the current indications that there are profitability and production gains to be made from increased NUE?

**Deliver Outputs of Activity B3:**

**Extent to which** the Science Coordinator appropriately organises research/sector partner communication activities and delivers upon the requirements of the actions and schedule of Section 9 “Program Implementation Plan” of the CEP.

**Extent to which** planned communications have been undertaken; extent of reach to targeted stakeholders; level of awareness and interest in contents; actions taken as a result of communication activities including access and use of resource and engagement in project activities.

**Program Materials (Products)**  
*Research and stakeholder adoption- What will the project produce?*

**Effectiveness** of specific fertiliser formulations/ smart blends in reducing losses and maintaining or increasing production under particular field conditions.

**Cost effectiveness** of EEFs under a range of management scenarios determined and **extent to which** findings are extended to producer programs/groups through resource materials & activities.

**Extent of change** in confidence of advisors and producers to attend demonstration activities and likelihood of using developed NUE DSS when making N fertiliser decisions.

**Extent to which** advisors and producers attend input/feedback activities and access resultant extension materials from websites.

**Evidence** that benchmarks/guidelines have been determined and are underpinned by research findings.

**Adoption** of NUE recommendations by industry BMP Programs- Fert$mart (dairy), Six Easy Steps (6ES) (Sugar) and CottonInfo (Cotton) resources.

**Number** of peer reviewed research reports prepared as a result of the MPfN Program.

**Number** of articles peer reviewed and published in science journals.

**Initiation Activities (Project Management & Planning)**  
*Underpinning structures and process to guide and support activities and outputs- What will be managed and how?*

**Representation and conduct of PMC**; meetings held and topics and decisions made; reaction by participants to meetings and evidence of influence and actions taken by members as a result of participation.

**Effectiveness** of Program Management Plan as the primary tool for implementing the Program and execution of timely activities to deliver Outputs in accordance with the Commonwealth Grant Agreement.

**Effectiveness** of PMP to monitor research partner progress and achieve KPIs within milestone dates.

**Effectiveness** of CEP as the primary tool for executing Program communications and extension activities in accordance with conditions outlined in the Commonwealth Grant Agreement.

**Effectiveness** of CEP in engaging key stakeholders in the Program’s activities to increase adoption of NUE best practices.

**Effectiveness** of the MEP in assisting the Program to monitor research partner KPI and Output obligations.

**Effectiveness** of the MEP as a tool of the PMC in assessing progress towards final Program outcomes throughout project implementation.

**The details of the M&E Data-base** (content, user-friendliness), access, downloads and other use statistics; feedback from users in usefulness and actions taken as a result of information gained.
### Additional Program Information

#### Table 1: Roles of key stakeholders involved in activities of the MPfN Program

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Program Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Agriculture &amp; Water Resources</td>
<td>Funding provider via Commonwealth Grant Agreement</td>
</tr>
<tr>
<td>MPfN Science Coordinator</td>
<td>Project Coordination &amp; Monitoring</td>
</tr>
<tr>
<td>Cotton Research and Development Corporation Dairy Australia</td>
<td>Manager/Program Sector Partner</td>
</tr>
<tr>
<td>Sugar Research Australia</td>
<td>Program Sector Partner</td>
</tr>
<tr>
<td>Hort Innovation Australia</td>
<td>Program Sector Partner</td>
</tr>
<tr>
<td>NSW DPI</td>
<td>Research Partner (x2)/ Project Collaborator</td>
</tr>
<tr>
<td>University of Southern Queensland - Centre for Engineering in Agriculture</td>
<td>Research Partner</td>
</tr>
<tr>
<td>Queensland University of Technology</td>
<td>Research Partner/ Project Collaborator</td>
</tr>
<tr>
<td>University of Melbourne</td>
<td>Research Partner (x2)/ Project Collaborator</td>
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<tr>
<td>QLD Government - Department of Environment &amp; Science</td>
<td>Research Partner / Project Collaborator</td>
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<tr>
<td>QLD Government - Department of Agriculture and Fisheries</td>
<td>Research Partner</td>
</tr>
<tr>
<td>Northern Territory Department of Primary Industry and Resources</td>
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</tr>
<tr>
<td>Tasmanian Institute of Agriculture (UTAS)</td>
<td>Research Partner/ Project Collaborator</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Project Collaborator (x2)</td>
</tr>
<tr>
<td>University of Queensland</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Southern Cross University Technical, Reporting, Analysis &amp; Project Services (TRAP)</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Agresearch (NZ)</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Cherry Growers of Australia</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Australian Mango Industry Assoc.</td>
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</tr>
<tr>
<td>Herbert Cane Productivity Services</td>
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</tr>
<tr>
<td>Farmacist</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Sunshine Sugar Agricultural Services</td>
<td>Project Collaborator</td>
</tr>
<tr>
<td>Industry Extension Programs (i.e. CottonInfo)</td>
<td>Industry extension &amp; resources</td>
</tr>
<tr>
<td>Private Farm Consultants</td>
<td>Industry extension, input, feedback &amp; adopters</td>
</tr>
<tr>
<td>Commercial Farm Advisors</td>
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<td>Farmer Groups/ farmers</td>
<td>Industry input, feedback &amp; adopters</td>
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#### Table 2: Research project end dates

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<tr>
<th>CRDC Agreement Code</th>
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<th>Final Reporting Date to CRDC</th>
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<tr>
<td>RRDP1712</td>
<td>More profit from nitrogen - enhancing nutrient use efficiency in cotton</td>
<td>NSW DPI</td>
<td>30 June 2021</td>
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<tr>
<td>RRDP1713</td>
<td>More Profit from Nitrogen - Optimising nitrogen and water interactions in cotton</td>
<td>USQ</td>
<td>30 June 2018</td>
</tr>
<tr>
<td>RRDP1714</td>
<td>More Profit from Nitrogen - Increasing nitrogen use efficiency in dairy pastures</td>
<td>QUT</td>
<td>30 November 2019</td>
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<tr>
<td>RRDP1715</td>
<td>More Profit from Nitrogen - Improving dairy farm nitrogen efficiency using advanced technologies</td>
<td>UoM</td>
<td>31 May 2020</td>
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<tr>
<td>RRDP1716</td>
<td>More Profit from Nitrogen - Quantifying the whole farm systems impact of nitrogen best practice on dairy farms</td>
<td>UoM</td>
<td>30 December 2020</td>
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<tr>
<td>RRDP1717</td>
<td>More Profit from Nitrogen - Improved nitrogen use efficiency through accounting for deep soil and mineralisable N supply, and deployment of Enhanced Efficiency Fertilisers to better match crop N demand</td>
<td>NSW DPI</td>
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<tr>
<td>RRDP1718</td>
<td>More Profit from Nitrogen - Smart blending of enhanced efficiency fertilisers to maximise sugarcane profitability</td>
<td>QDES</td>
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<td>RRDP1719</td>
<td>More Profit from Nitrogen - New technologies and managements: transforming nitrogen use efficiency in cane production.</td>
<td>QDAF</td>
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<td>RRDP1720</td>
<td>More Profit from Nitrogen - Optimising nutrient management for improved productivity and fruit quality in mangoes</td>
<td>NTDPIR</td>
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<tr>
<td>RRDP1721</td>
<td>More Profit from Nitrogen - Optimising nutrient management for improved productivity and fruit quality in cherries</td>
<td>TIA</td>
<td>30 June 2021</td>
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<td>RRDP1901</td>
<td>More profit from Nitrogen - Nitrogen use efficiency indicators for the Australian cotton, sugar, dairy and horticulture industries</td>
<td>CSIRO</td>
<td>30 June 2019</td>
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**Table 3**

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<tr>
<th>Milestone</th>
<th>Partner Reporting Schedule to CRDC</th>
<th>CRDC Reporting Schedule to DoA</th>
</tr>
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<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>31/05/2017</td>
<td>03/07/2017</td>
</tr>
<tr>
<td>3</td>
<td>30/11/2017</td>
<td>01/02/2018</td>
</tr>
<tr>
<td>4</td>
<td>31/05/2018</td>
<td>13/08/2018</td>
</tr>
<tr>
<td>5</td>
<td>30/11/2018</td>
<td>04/02/2019</td>
</tr>
<tr>
<td>6</td>
<td>31/05/2019</td>
<td>15/07/2019</td>
</tr>
<tr>
<td>7</td>
<td>30/11/2019</td>
<td>24/01/2020</td>
</tr>
<tr>
<td>8</td>
<td>31/05/2020</td>
<td>30/06/2020</td>
</tr>
<tr>
<td>9</td>
<td>30/11/2020</td>
<td>05/02/2021</td>
</tr>
<tr>
<td>10</td>
<td>30/06/2021</td>
<td>30/09/2021</td>
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</tbody>
</table>
Attachment 3

**Nitrogen Use Efficiency Indicators for the Australian Cotton, Grains, Sugar, Dairy and Horticulture Industries**, Diogenes L. Antille (CSIRO) & Philip W. Moody (University of Queensland).
Nitrogen Use Efficiency Indicators for the Australian Cotton, Grains, Sugar, Dairy and Horticulture Industries

Diogenes L. Antille¹, Philip W. Moody²

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²The University of Queensland, School of Agriculture and Food Sciences, Brisbane, QLD, Australia, E: smsphil1@gmail.com

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 N₂O 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 N₂O (and N₂) 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](image-url)

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 N₂O 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 \( \approx 40\% \) (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 \( \approx 40\% \)) 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 (%$\text{W}$/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, $\text{W}$/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:

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

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 (%$\text{W}$/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:

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

$$PFP_N = \frac{Y_N}{N_R}$$  \hspace{1cm} (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:

$$PE_N = \frac{(Y_{N=0} - Y_N)}{(U_{N=0} - U_N)}$$  \hspace{1cm} (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 (Benzi 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).

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Acronym</th>
</tr>
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<tbody>
<tr>
<td>N utilization efficiency: the efficiency with which a crop utilizes accumulated N to produce a unit of crop growth.</td>
<td>t DM kg(^{-1}) crop N</td>
<td>(NU_{UE})</td>
</tr>
<tr>
<td>Fertilizer N uptake efficiency: the efficiency with which applied N fertilizer is accumulated in crop biomass.</td>
<td>kg crop N kg(^{-1}) fertilizer N applied</td>
<td>(NU_{FERT})</td>
</tr>
<tr>
<td>Agronomic efficiency of fertilizer N: the efficiency with which fertilizer N is used to produce crop yield.</td>
<td>t cane yield kg(^{-1}) fertilizer N applied</td>
<td>(AE_{FERT})</td>
</tr>
<tr>
<td>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.</td>
<td>t cane yield kg(^{-1}) fertilizer N applied</td>
<td>(AppAgronEff)</td>
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</tbody>
</table>

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, \(NU_{FERT}\) 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 \(NU_{FERT}\), \(AE_{FERT}\), 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:

\[
\text{Average NUE} = \frac{(\text{DM}_{N=0} - \text{DM}_{N=N})}{N_R}
\]  

where: \(\text{DM}_{N}\) and \(\text{DM}_{N=0}\) 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.

\[
\text{Marginal NUE} = \frac{(\text{DM}_{N(x)} - \text{DM}_{N(x-1)})}{(N(x) - N(x-1))}
\]  

where: \(\text{DM}_{N(x)}\) and \(\text{DM}_{N(x-1)}\) 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:

\[
\text{N surplus} = N_i - N_0
\]  

where: N surplus is the difference between total N inputs \((N_i)\) and total N outputs \((N_0)\), 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.
\[ Apparent \, N \, recovery = \frac{\text{Grass N uptake}}{N_i} \] (12)

where: grass N uptake is derived from DM yield (kg ha\(^{-1}\)) and N content (\(\%, \frac{W}{W}\)) 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):

\[
PFP_N = \frac{\text{Fruit yield per tree}}{N_R}
\]  

(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.

\[
PNB = \frac{N_{\text{FRUIT}}}{N_R}
\]  

(14)

where: \(PNB\) is partial N balance (kg kg\(^{-1}\)), \(N_{\text{FRUIT}}\) is N removed in fruit per tree (kg) and \(N_R\) is the N application rate (kg) per tree. \(N_{\text{FRUIT}}\) is estimated from the mean N concentration in fruit (\(\% \text{, } \frac{W}{W}\)) 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 \(^{15}\text{N}\).

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):

\[
NUPE = \frac{U_N}{N_R}
\]  

(15)

where: \(NUPE\) 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 (\(\% \text{, } \frac{W}{W}\)) 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 \(NUPE\) 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:

\[
\text{iNUE} = \frac{\text{Fruit yield per tree}}{U}
\]

(16)

where: \(\text{iNUE}\) is internal N use efficiency, \(\text{fruit yield per tree}\) 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 \(\text{iNUE}\) 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 \(\text{NU}_{PE}\) and \(\text{iNUE}\) 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:

\[ y = a + bx - cx^2 \]  

(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):

\[ \frac{dy}{dx} = b - 2cx' = 0 \]  

(18)

due to:

\[ x' = \frac{b}{2c} \]  

(19)

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

\[ b - 2cx' = P_R \]  

(20)

and,

\[ P_R = \frac{P_N}{P_C} \]  

(21)

due to:

\[ MERN = \frac{b-P_R}{2c} \]  

(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.

**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.
**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.

<table>
<thead>
<tr>
<th>Location</th>
<th>---</th>
<th>Northern NSW</th>
<th>QLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Query</td>
<td>Unit</td>
<td>Nil N Rate 1</td>
<td>Rate 2</td>
</tr>
<tr>
<td>Fertilizer rate</td>
<td>kg N ha⁻¹</td>
<td>0 100 300</td>
<td>0 108 145</td>
</tr>
<tr>
<td>Miliable cane</td>
<td>tonnes DM ha⁻¹</td>
<td>10.9 14.4 18.0</td>
<td>10.3 21.4 22.2</td>
</tr>
<tr>
<td>Miliable cane-N</td>
<td>tonnes FW ha⁻¹</td>
<td>39.8 54.10 68.8</td>
<td>34.3 71.3 74.0</td>
</tr>
<tr>
<td>Above-ground trash</td>
<td>tonnes DM ha⁻¹</td>
<td>6.01 7.81 8.92</td>
<td>3.70 6.01 7.16</td>
</tr>
<tr>
<td>Above-ground trash-N</td>
<td>% (w/w)</td>
<td>0.53 0.69 0.78</td>
<td>0.488 0.493 0.513</td>
</tr>
<tr>
<td>Fertilizer + application cost</td>
<td>AUD ha⁻¹</td>
<td>--- --- ---</td>
<td>--- --- ---</td>
</tr>
<tr>
<td>Gross Margin</td>
<td>AUD ha⁻¹</td>
<td>--- --- ---</td>
<td>--- --- ---</td>
</tr>
</tbody>
</table>

**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.

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

**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 ¹⁵N 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.

<table>
<thead>
<tr>
<th>Location</th>
<th>---</th>
<th>Mango, Northern Territory</th>
<th>Cherry, Tasmania</th>
</tr>
</thead>
<tbody>
<tr>
<td>Query</td>
<td></td>
<td>Nil N</td>
<td>Rate 1</td>
</tr>
<tr>
<td>Fertilizer rate</td>
<td>kg N ha⁻¹</td>
<td>0</td>
<td>12.5</td>
</tr>
<tr>
<td>Ungraded fruit</td>
<td>tons DM ha⁻¹</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Ungraded fruit</td>
<td>tons FW ha⁻¹</td>
<td>19.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Ungraded fruit-N</td>
<td>% (w/w), DM</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td>Ungraded fruit-N</td>
<td>% (w/w), FW</td>
<td>0.084</td>
<td>0.093</td>
</tr>
<tr>
<td>Unharvested biomass (annual pruning)</td>
<td>tons DM ha⁻¹</td>
<td>1.1</td>
<td>---</td>
</tr>
<tr>
<td>Unharvested biomass (annual litter)</td>
<td>tons DM ha⁻¹</td>
<td>1.6</td>
<td>---</td>
</tr>
<tr>
<td>Unharvested biomass (annual pruning)-N</td>
<td>% (w/w), dry basis</td>
<td>0.60</td>
<td>---</td>
</tr>
<tr>
<td>Unharvested biomass (annual litter)-N</td>
<td>% (w/w), dry basis</td>
<td>0.71</td>
<td>---</td>
</tr>
<tr>
<td>Fertilizer + application cost</td>
<td>AUD ha⁻¹</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>Gross Margin</td>
<td>AUD ha⁻¹</td>
<td>12790</td>
<td>12325</td>
</tr>
</tbody>
</table>
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.

\[ NU_{t}E = \frac{TB}{U} \]  
(23)

where: \( NU_{t}E \) 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.

\[ NU_{p}E = \frac{U}{N_{R}} \]  
(24)

where: \( NU_{p}E \) 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\(^{-1}\)).

\[ AE = NU_{t}E \times NU_{p}E \times HI \]  
(25a)

where: \( HI \) is harvest index; therefore:

\[ AE = \frac{TB}{U} \times \frac{U}{N_{R}} \times \frac{Y}{TB} \]  
(25b)

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

\[ AE = \frac{Y}{N_{R}} \]  
(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

\[ MR_{F} = \frac{\text{Economic return}}{N_{R}} \]  
(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.
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).

<table>
<thead>
<tr>
<th>Proposed NUE indicator</th>
<th>Acronym</th>
<th>Focus</th>
<th>Factors affecting</th>
<th>(†) Interpretation</th>
<th>Cross-industry usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer N utilization efficiency</td>
<td>$NU_PE$</td>
<td>Productivity</td>
<td>Environmental constraints to crop production; varietal/cultivar differences; general crop and soil husbandry.</td>
<td>Crop’s ability to transform N taken-up from all sources into total biomass.</td>
<td>Limited.</td>
</tr>
<tr>
<td>Fertilizer N uptake efficiency</td>
<td>$NU_PE$</td>
<td>Productivity, Environmental</td>
<td>Off-site N losses.</td>
<td>Uptake per unit of N applied. If calculated by the difference method, proportion of N applied taken-up by the crop.</td>
<td>Benchmarks cropping system NUE in terms of fertilizer N recovery.</td>
</tr>
<tr>
<td>Agronomic efficiency of applied fertilizer N</td>
<td>$AE$</td>
<td>Productivity, Environmental</td>
<td>Environmental constraints to crop production; varietal/cultivar differences; general crop and soil husbandry; off-site N losses.</td>
<td>Productivity per unit of N applied. If calculated by the difference method, then this shows net productivity per unit of N.</td>
<td>Benchmarks cropping system NUE in terms of harvested product produced per unit of fertilizer N applied.</td>
</tr>
<tr>
<td>Marginal return on applied fertilizer N</td>
<td>$MR_F$</td>
<td>Profitability</td>
<td>Relativity of fertilizer cost to product value (price ratio).</td>
<td>Economic return per unit of N applied</td>
<td>Benchmarks cropping system NUE in terms of harvested product economic return per unit fertilizer N applied.</td>
</tr>
</tbody>
</table>
Figure 3: Conceptual diagram illustrating the derivation of ‘average’ and ‘marginal’ nitrogen (N) use efficiency (NUE) indicators; N₁ and N₂ 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.

<table>
<thead>
<tr>
<th>Crop, location</th>
<th>Cropping season</th>
<th>Ns</th>
<th>Fertilizer type, placement</th>
<th>( N_U )E</th>
<th>Average ( N_U )E</th>
<th>Marginal ( N_U )E</th>
<th>( A_E )</th>
<th>Average ( M_R )F</th>
<th>Marginal ( M_R )F</th>
<th>HI (DM)</th>
<th>HI (N)</th>
<th>Nil N crop uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Month</td>
<td>kg N ha(^{-1})</td>
<td>---</td>
<td>kg kg(^{-1})</td>
<td>kg kg(^{-1})</td>
<td>kg kg(^{-1})</td>
<td>$ kg(^{-1})</td>
<td>$ kg(^{-1})</td>
<td>---</td>
<td>---</td>
<td>kg ha(^{-1})</td>
<td></td>
</tr>
<tr>
<td>Sugarcane, QLD</td>
<td>12</td>
<td>0, 108, 145</td>
<td>Urea, subsurface band</td>
<td>385</td>
<td>0.28</td>
<td>0.29</td>
<td>82.1</td>
<td>11.52</td>
<td>0.79</td>
<td>0.76</td>
<td>0.52</td>
<td>36</td>
</tr>
<tr>
<td>&quot;Sugarcane, NSW&quot;</td>
<td>12</td>
<td>0, 100, 300</td>
<td>Urea, subsurface band</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>76.7</td>
<td>9.44</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cotton, QLD</td>
<td>6</td>
<td>0, 125, 180</td>
<td>Urea, subsurface band</td>
<td>46</td>
<td>0.46</td>
<td>0.30</td>
<td>11</td>
<td>2.25</td>
<td>0.57</td>
<td>0.67</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>Cotton, NSW</td>
<td>6</td>
<td>0, 112, 292</td>
<td>Urea, subsurface band</td>
<td>50.7</td>
<td>0.62</td>
<td>0.46</td>
<td>17.06</td>
<td>7.96</td>
<td>1.61</td>
<td>0.47</td>
<td>0.54</td>
<td>160</td>
</tr>
<tr>
<td>Dairy, NNSW</td>
<td>12</td>
<td>0, 410, 495</td>
<td>Urea, broadcast</td>
<td>29.7</td>
<td>0.60</td>
<td>0.90</td>
<td>28.3</td>
<td>5.44</td>
<td>3.08</td>
<td>0.94</td>
<td>0.99</td>
<td>212</td>
</tr>
<tr>
<td>Dairy, Central NSW</td>
<td>12</td>
<td>0, 120, 240</td>
<td>Urea, broadcast</td>
<td>40</td>
<td>0.78</td>
<td>0.66</td>
<td>25.1</td>
<td>11.56</td>
<td>11.82</td>
<td>0.99</td>
<td>0.99</td>
<td>272</td>
</tr>
<tr>
<td>Dairy, VIC</td>
<td>12</td>
<td>0, 240, 480</td>
<td>Urea, broadcast</td>
<td>24.9</td>
<td>0.67</td>
<td>0.53</td>
<td>16.8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>133</td>
</tr>
<tr>
<td>Mango, NT</td>
<td>12</td>
<td>0, 12.5, 25</td>
<td>Ammonium sulphate, drip</td>
<td>161.8</td>
<td>0.02</td>
<td>-0.04</td>
<td>8</td>
<td>3.2</td>
<td>N/A</td>
<td>0.53</td>
<td>0.51</td>
<td>40</td>
</tr>
<tr>
<td>Cherry, TAS</td>
<td>12</td>
<td>0, 90</td>
<td>CN, drip</td>
<td>92.2</td>
<td>0.11</td>
<td>N/A</td>
<td>28.3</td>
<td>129.8</td>
<td>N/A</td>
<td>0.52</td>
<td>0.37</td>
<td>74</td>
</tr>
</tbody>
</table>
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 $NU_l E$**

With the exception of the horticultural tree crops, average $NU_l E$ 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 $NU_l E$ 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, $NU_l E$ 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 NUE 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 NUE 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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REFERENCES


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 \(\text{NUtE}\), (2) fertilizer N uptake efficiency \(\text{NUPE}\), (3) agronomic efficiency of applied fertilizer N \(\text{AE}\), and (4) marginal return on applied fertilizer N \(\text{MR}\). 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.