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Assessing water quality for cropping management practices: A new approach for dissolved inorganic nitrogen discharged to the Great Barrier Reef

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ABSTRACT

Applications of nitrogen (N) fertiliser to agricultural lands impact many marine and aquatic ecosystems, and improved N fertiliser management is needed to reduce these water quality impacts. Government policies need information on water quality and risk associated with improved practices to evaluate the benefits of their adoption. Policies protecting Great Barrier Reef (GBR) ecosystems are an example of this situation. We developed a simple metric for assessing the risk of N discharge from sugarcane cropping, the biggest contributor of dissolved inorganic N to the GBR. The metric, termed NiLRI, is the ratio of N fertiliser applied to crops and the cane yield achieved (i.e. kg N (t cane)$^{-1}$). We defined seven classes of water quality risk using NiLRI values derived from first principles reasoning. NiLRI values calculated from (1) results of historical field experiments and (2) survey data on the management of 170,177 ha (or 53%) of commercial sugarcane cropping were compared to the classes. The NiLRI values in both the experiments and commercial crops fell into all seven classes, showing that the classes were both biophysically sensible (*c.f.* the experiments) and relevant to farmers' experience. We then used machine learning to explore the association between crop management practices recorded in the surveys and associated NiLRI values. Practices that most influenced NiLRI values had little apparent direct impact on N management. They included improving fallow management and reducing tillage and compaction, practices that have been promoted for production rather than N discharge benefits. The study not only provides a metric for the change in N water quality risk resulting from adoption of improved practices, it also gives the first clear empirical evidence of the agronomic practices that could be promoted to reduce water quality risk while maintaining or improving yields of sugarcane crops grown in catchments adjacent to the GBR. Our approach has relevance to assessing the environmental risk of N fertiliser management in other countries and cropping systems.

1. Introduction

The expansion and intensification of agriculture has increased the discharge of nitrogen (N) to marine and aquatic ecosystems (Schlesinger, 2009; Zhang et al., 2015; Martínez-Dalmau et al., 2021), causing eutrophication in many parts of the world (Howarth, 2008; Fowler et al., 2013; Kroon et al., 2016). Improving the management of N inputs to farms is an important step in reducing these discharges and consequent ecosystem impacts. A range of measures is available to encourage farmers to improve N management, including education, incentives, subsidies, market-based instruments and/or regulation (Kroon et al., 2016). The implementation of these measures is often guided or accompanied by programs to evaluate the resultant reduction in N discharged. Ideally the reduction in N discharge is evaluated by direct measurement of water quality. However, this approach is expensive and attribution to individual farms or fields is difficult because of the diffuse nature of the N discharges from agriculture, as well as spatial and temporal variability in the results and the impracticality of monitoring at a field scale (Dowd et al., 2008; Duncan, 2017; Davis et al., 2021). An alternative is to monitor adoption of improved practices by farmers, then associate these with water quality outcomes. This approach has been adopted in many countries, including some Nordic countries (Hellsten et al., 2019), USA (Jones et al., 2018) and Australia (State of Queensland, 2018).

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In Australia, monitoring changes in farmers' management practices is an important part of government policies to protect World Heritage listed Great Barrier Reef (GBR) ecosystems from the impact of dissolved N discharged from nearby cropping lands. Application of N fertilisers to sugarcane crops is a major driver of dissolved inorganic N discharges to the GBR (Thorburn et al., 2013; Thorburn and Wilkinson, 2013) and regulations have been enacted to limit N application rates to these crops (State of Queensland, 2020). In addition, targets have been set in policy for the adoption of improved management practices (State of Queensland, 2018). The change in farmers' land management is evaluated within a monitoring and evaluation program known as the "Paddock-to-Reef" program (Carroll et al., 2012; Australian and Queensland Governments, n. d.(a)). Information on farmers' management practices is obtained by surveying farmers who participate in programs facilitating improved farm management (Australian and Queensland Governments, 2020; McCosker and Northey, 2015). For a particular area of land (e.g. a field or farm) the practices implemented are used to determine different levels of water quality risk. There are four water quality risk classes:

- *Lowest risk*: Innovative practices, possibly unproven
- *Moderate-low risk*: Best practice, above industry standard
- *Moderate risk*: Minimum standard, industry standard
- *High risk*: Below industry standard

For dissolved N discharges, the main practice determining the water quality risk class is the extent to which farmers match N fertiliser applications to crop yield expectations (Australian and Queensland Governments, n. d.(b); McCosker and Northey, 2015).

The Australian sugarcane industry has clearly defined, and industry supported guidelines for N fertiliser application rates, known as SIX EASY STEPS™ (Schroeder et al., 2014), which are a benchmark for the different risk classes. The SIX EASY STEPS™ (6ES) program is essentially a two-phase process with the first phase (Steps 1 to 4 of the six) resulting in N fertiliser guidelines for a field based on a regional crop production potential, together with fallow management practices and soil organic carbon concentrations of the field. Applying N fertiliser in accordance with the first phase of 6ES results in a *Moderate* water quality risk classification. Reducing the N water quality risk in the Paddock-to-Reef program classes relies primarily on matching N fertiliser application rates to historical yields in a field or management zone. The underlying logic for this approach is assumptions that (1) yields at these scales should be less than regional yield potential and (2) lower yields should require lower N fertiliser applications (Bell and Moody, 2014). The first assumption is usually, but not always true (Schroeder et al., 2014; Larsen and Dougall, 2017). The second assumption is based on the logic that there is a positive correlation between sugarcane yield and the optimum amount of N fertiliser required to achieve that yield, e.g. smaller crops need less N. This logic is a common basis of fertiliser recommendations (Morris et al., 2018; Puntel et al., 2018); however, it is not necessarily valid. That is, low yielding crops do not necessarily require less N (per unit of production) than higher yielding crops. Further, since the development of the Paddock-to-Reef risk framework the optimum amount of N for sugarcane crops has been shown to be poorly correlated to yield (Thorburn et al., 2018). Thus, reducing N fertiliser rates in a management zone, for whatever reason, may reduce yields through N deficiency. Given the importance of cane production to the profitability of all parts of the sugarcane value chain this outcome is of concern to the sugar industry (Canegrowers, 2020). Yet there is empirical evidence that N applications can be reduced relative to conventional practice without loss of yield (Thorburn et al., 2011; Webster et al., 2012; Rohde et al., 2013a,b) although the factors underlying the maintenance of yields at lower N applications are not yet fully understood.

Given this situation it is unclear what practices Australian sugarcane farmers should adopt to both reduce their N water quality risk and minimise the risk of yield loss. This lack of clarity is a barrier to the sugarcane industry supporting water quality policies and regulations (Canegrowers, 2020). Rather than stipulate practices that need to be adopted to reduce water quality risk, it would be preferable to have a metric of N water quality risk that has a more direct link to N losses. If water quality risk could be widely assessed with such a new metric, it may be possible to then gain insights into the management practices that are associated with lower risk, which in turn could inform extension efforts to improve management and water quality. Accordingly, in this study, we considered some possible N water quality risk metrics to find one suitable for application within the Paddock-to-Reef program. We then developed water quality risk classes, based on ranges of the metric's values that are relevant to Australian sugarcane production systems. These classes were developed from first principles then assessed against results from field experiments. Finally, we determined the values of the metric farmers have achieved in commercial sugarcane production from data obtained through Paddock-to-Reef surveys, and used machine learning to identify associations between farmer-adopted practices and the new water quality risk classes.

2. Water quality risk metric frameworks

2.1. N surplus

The N surplus – the difference between N inputs to, and offtake in agricultural produce from a field or farm – is a commonly used water quality risk metric (Klages et al., 2020). If N inputs are greater than crop uptake, surplus N can be stored in the soils. In the long term however, the storage capacity of the soil becomes saturated and surplus N is lost to the environment. Thus, lower N surpluses indicate lower N losses. This concept is relevant to GBR catchments as N surpluses are correlated to dissolved inorganic N discharges (Thorburn and Wilkinson, 2013).

Use of N surplus as a water quality index has some drawbacks. Calculating N surplus requires information on the mass of N in harvested produce, which is the product of the mass of the produce or other offtake from the field and its N concentration. Mass of the produce is usually known. However, N concentrations of produce may not be measured. Large, unmeasured variation in N concentrations result in uncertainties in calculated N surpluses that reduce its accuracy and usefulness as a water quality risk index when applied at scale (Klages et al., 2020). This variation can occur in many agricultural systems, including dairy (Gourley et al., 2012) and sugarcane (Thorburn et al., 2011; Bell and Garside, 2014). There is another substantial source of variation in sugarcane production arising from the management of crop residues. Sugarcane crop residues may either be left in the field or removed, usually by burning. When they are burnt the mass of N in the residues, which can be similar to that in harvested cane, needs to be included in the calculation of N surplus (i.e. N fertiliser *minus* N in cane *minus* N in residues). There is considerable variability in both the amount and N concentration, and thus N mass in burnt residues (Mitchell et al., 2000). This will increase the uncertainties in calculated N surpluses for sugarcane production, further reducing its usefulness as a water quality risk index.

Another characteristic of N surplus for major crops in GBR catchments is that it is highly correlated with N fertiliser application rates (Fig. 1). Thus, the complexity of estimating N surplus adds little extra information about water quality risk compared to information on N fertiliser applications.

2.2. Nitrogen use efficiency

There are multiple definitions of nitrogen use efficiency (NUE); however, for our purpose we define NUE as sugarcane yield relative to N fertiliser applications (t cane (kg N)$^{-1}$) also known as the partial factor productivity of N. NUE is traditionally used as a concept for enhancing productivity, for example asking the question: "What can be done to

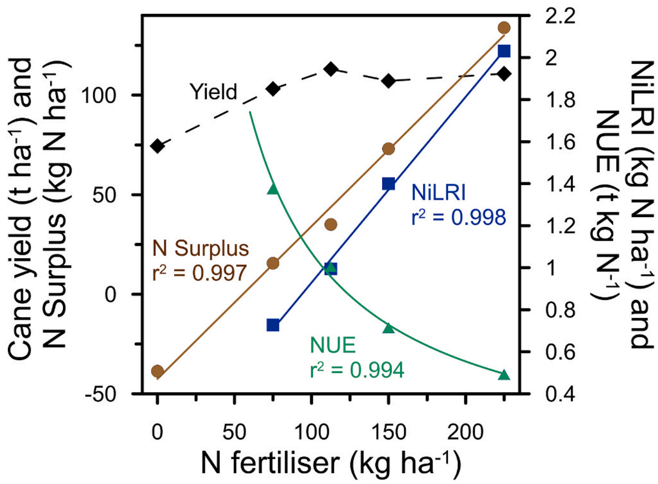

Fig. 1. The effect of N fertiliser application rate on sugarcane yields and various water quality metrics. Data are averaged over five crops. The metrics are N surplus (difference between N fertiliser applied and N exported in cane), Nitrogen Loss Risk Index (NiLRI: N fertiliser applied/yield) and Nitrogen Use Efficiency (NUE: Yield/N fertiliser applied). After Thorburn and Wilkinson (2013).

increase yield for a given application of N fertiliser?" Its simplicity and focus on increasing productivity make it an attractive concept to farmers and industry.

NUE has also been used as a water quality risk index because as N fertiliser management becomes more "efficient" there should be less N lost to the environment (Martínez-Dalmau et al., 2021). Unlike N surplus, calculation of NUE relies on fewer assumptions so it lends itself to being a widely applied water quality metric. However, NUE is inversely related to N surplus (Fig. 1) and the inverse nature of the relationship – that *increased* efficiency leads to *reduced* risk – could cause difficulty in communicating water quality risk through NUE. Further, highest NUE values are achieved at lowest N application rates that result in reduced yields (Fig. 1). Thus the "message" of increasing NUE to reduce water quality risk can be interpreted as the need to reduce yield, which is a concern to the Australian sugar industry (Schroeder et al., 2018).

2.3. Nitrogen Loss Reduction Index (NiLRI)

Given these potential problems with N surplus and NUE as water quality risk metrics, we propose using the amount of fertiliser N applied relative to yield (kg N (t cane)$^{-1}$), i.e. the inverse of NUE, as a risk metric. We call this metric the Nitrogen Loss Reduction Index (NiLRI). NiLRI is numerically the same as the "N requirement" term in equations calculating N fertiliser applications rates (Thorburn et al., 2011; Schroeder et al., 2014; Morris et al., 2018):

N rate (kg N ha^{-1}) = yield (t cane ha^{-1}) x *N requirement* (kg N t^{-1}).

While its use in calculating N fertiliser rates has not been linked to N losses to the environment, NiLRI (a) is closely related to N surplus (Fig. 1) and thus to N losses, (b) has the simplicity of calculating NUE, and (c) is directly related to water quality risk; i.e. the higher the value of NiLRI the greater the risk.

3. Deriving NiLRI classes for N water quality risk

3.1. Overview

Using NiLRI values (or any other metric) as the basis of a water quality risk framework requires that NiLRI values be developed to define different classes of water quality risk. We derive NiLRI values for different scenarios about N applications and yields for sugarcane cropping in GBR catchments, then use these NiLRI values as "reference points" for the boundaries between water quality risk classes. We test the plausibility of the classes by comparing them to NiLRI values calculated for a large number of previous N fertiliser response experiments.

Sugarcane is a semi-perennial crop that is harvested multiple times.[1] The preceding conditions (e.g. fallows) and management of the first crop (known as the "plant crop") is usually different to the subsequent crops (known as "ratoon crops"). Thus, we derive NiLRI-based risk classes separately for ratoon and plant crops.

3.2. Production scenarios for deriving NiLRI reference points

3.2.1. Ratoon crops

The 6ES guidelines provide a reference for likely maximum N application rates to sugarcane crops because N management regulations for sugarcane (State of Queensland, 2020) closely mirror the first phase of 6ES. The 6ES guidelines vary with soil organic carbon (SOC) – lower N requirement for soils with higher SOC – so precisely calculating these N rates at a broad scale is difficult. However, in GBR catchments >80% of sugarcane is grown on soils that have SOC between 0.4 and 1.6% (Schroeder et al., 2014). If we assume SOC is 1% for calculation of N application rates using 6ES, the variation in N rate for soils with 0.4% or 1.6% SOC is only ± 10 kg ha^{-1} compared with the rate for soils with 1%. This variation is acceptable uncertainty for our purpose.

For cane yields, regional average yields are published annually in various Australian sugar industry reports (Appendix 1) and these data can be used to define "average" crop production. Thus, the N applications from the first phase of the 6ES guidelines together with regional average yields provide a reference point for NiLRI values.

However, it is clear some farms or fields achieve yields greatly exceeding the regional average (Schroeder et al., 2014; Larsen and Dougall, 2017). Provided N applications to these highly productive crops are consistent with the first phase of 6ES guidelines, NiLRI values should be lower than for areas of average production. So it will be useful to use these high yields as a reference for the lower bounds of possible NiLRI risk classes. We take the yields of these highly productive situations to be the regional yield potential specified in the 6ES guidelines (Schroeder et al., 2014). Thus, the N applications from the first phase of the 6ES guidelines together with regional potential yields provide another reference point for NiLRI values.

3.2.2. Plant crops

Deriving NiLRI reference points for plant crops is more complicated than for ratoon crops because of the diversity of field conditions preceding planting a crop. A plant crop is commonly preceded by a fallow, and there are many possible fallow management practices. These practices affect both N fertiliser management and yield of the subsequent plant crop.

There are two process that may increase yields of plant crops relative to ratoon crops. Growing a legume crop during a fallow improves soil health and boosts yields of subsequent plant crops (Garside and Bell, 2011). Also, plant crops are usually allowed to grow longer and thus attain higher yields than ratoon crops before harvesting. We assume the total yield increase in plant crops from these two factors is 20%. This increase could occur in fields with high productive potential (equivalent to ratoon crops achieving regional yield potential) or average production potential (ratoon crops achieving average yields). This logic provides the yield component for two reference points for plant crop NiLRI values.

[1] In Australia, sugarcane is commonly harvested 15–18 months after it is planted. The crop is then allowed to re-grow (i.e. ratoon) and harvested approximately annually. (The harvesting season in Australia is approximately June to December.) The crop loses vigour after 3–6 harvests. When this occurs, it is destroyed and the field is commonly, although not always, fallowed for ~6 month until the next crop is planted.

N contained in residues of a fallow legume crop will off-set the N fertiliser applications needed for a plant crop, so N applications will be reduced relative to ratoon crops. The reductions can be high enough, depending on the legume species and biomass produced (Schroeder et al., 2014), that no N fertiliser needs to be applied. In practice, farmers do not have a convenient and reliable way to determine the legume biomass. Thus, they are reluctant to reduce N rates to this extent. It is also possible to harvest grain from fallow legume crops. This reduces N contained in residues, and thus the possible reduction in N fertiliser applications to plant crops, as much of the N in above ground biomass of legume crops is in the grain. In these situations, plant crops following a legume may receive around 80 kg ha^{-1} less N fertiliser than ratoon crop guidelines (Schroeder et al., 2014) and so we assume a reduction in N applications of 80 kg ha^{-1}.

While plant crops are commonly preceded by a fallow, they can also be established immediately after a ratoon crop (known as a "plough-out/replant" crop). In this circumstance, the plant crop will generally grow for a similar time to ratoon crops before being harvested and neither receive a post-fallow yield "boost" nor input of N from a legume, so has the same production expectations and N fertiliser requirements as a ratoon crop.

3.3. Reference point values

Yields and 6ES N guidelines vary between regions and may affect NiLRI reference points. Yields and 6ES N guidelines are similar in the Wet Tropics, Herbert and Southern regions so these will be grouped together. Climate and irrigation water availability underpin higher production potential in the Burdekin and Mackay regions (Schroeder et al., 2018) thus we will develop NiLRI reference points separately for these two regions.

Table 1
Ratoon crop cane yields and N fertiliser application rates and resultant values of the Nitrogen Loss Reduction Index (NiLRI) and N surplus for different regions assuming either potential or actual yields.

Region	Production assumption[a]	Cane yield (t ha^{-1})	N fertiliser[b] (kg ha^{-1})	NiLRI (kg N (t cane)$^{-1}$)	N surplus[c] (kg ha^{-1})
Mossman, Mulgrave, Innisfail, Tully, Herbert, Bundaberg	Potential yield	120	140	1.17	68
Mackay, Proserpine	Potential yield	130	150	1.15	72
Burdekin	Potential yield	170	200	1.18	98
Mossman, Mulgrave, Innisfail, Tully, Herbert, Bundaberg	Average yield	80	140	1.75	92
Mackay, Proserpine	Average yield	70	150	2.14	108
Burdekin	Average yield	115	200	1.74	131

[a] Potential yields are the regional yield potentials identified by Schroeder et al. (2014) and average yields come from Canegrowers annual reports (Appendix 1).
[b] N fertiliser application rates are the rates resultant from phase 1 (Steps 1 to 4) of the 6ES assuming a soil organic carbon content of 1%.
[c] The N surplus is calculated assuming the N concentration of harvested sugarcane is 0.6%.

3.3.1. Ratoon crops

Assuming **potential** yields (i.e. 120-170 t ha^{-1}, Table 1) and 6ES N guidelines (applications of 140–200 kg N ha^{-1}) results in NiLRI values from 1.15 to 1.18 between the three regions. This similarity across regions is not surprising because 6ES N guidelines are related to regional production potential, e.g. both yield potential and N guidelines are higher in the highly productive Burdekin than other regions. From these results we take a NiLRI value of 1.2 to provide a reference point for water quality risk for very high crop production being obtained with the application of the 6 ES guidelines (phase 1). We know NiLRI values this low (and lower) occur in experiments (Fig. 2a), confirming that this NiLRI value is a biophysically valid reference point.

Assuming **average** yields (over recent years) and 6ES recommended N rates, NiLRI reference values are ~1.75 kg N (t cane)$^{-1}$ for the Burdekin and Wet Tropic-Herbert-Southern regions but higher (2.14 kg N (t cane)$^{-1}$) for Mackay (Table 1). The similarity between the Burdekin and Wet Tropics-Herbert regions is expected, because of both the yield potential and N guidelines are higher in the Burdekin region. The higher NiLRI reference value in the Mackay region reflects the lower average yield achieved relative to the potential yield than in the other regions. More specifically, the ratio of average to potential yield in Mackay is 54%, compared with 67% for the other regions. If actual yields were 15 t ha^{-1} higher in Mackay the NiLRI reference value would be 1.76, similar to the other regions. It is likely this yield increase could be achieved by better use and management of irrigation water (discussed below). We take a NiLRI value of 1.7 to provide a reference point for water quality risk for average crop production being obtained with the application of the 6ES guidelines (phase 1). As with high crop production, NiLRI reference values this high, and higher have been found in experiments (Fig. 2a).

3.3.2. Plant crops

For plant crops following a legume fallow that receive 80 kg N ha^{-1} less than ratoons crops and achieve regional **potential** yields, NiLRI values range from 0.42 to 0.59 across the different regions (Table 2). We take the reference point to be 0.50. There is experimental evidence that NiLRI values equal to, or lower than the reference point are achievable (Fig. 2b). For **average** yielding crops following a legume fallow the range is 0.63–0.87 (Table 2), and we take the reference point to be 0.70 which is also achieved in experiments (Fig. 2b).

For "plough-out/replant" crops, which do not have the yield boost

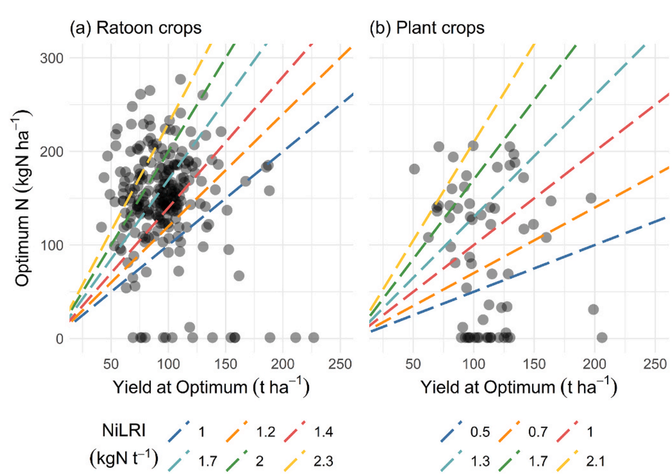

Fig. 2. Relationship between the optimum N fertiliser application rates and yields at that optimum N rate for (a) ratoon and (b) plant sugarcane crops in N response experiments conducted in the Australian sugar industry (derivation of these data describe in Appendix 2). The ratio of optimum N rates to yields at that rate define the NiLRI value at the optimum. The dashed lines show the boundaries of the seven NiLRI classes described in Tables 3 and 4 for ratoon and ratoon crops, respectively.

Table 2
Plant crop cane yields and N fertiliser application rates and resultant values of the Nitrogen Loss Reduction Index (NiLRI) and N surplus for three regions assuming either potential or average yields, both of which are 20% higher than ratoon crop yields. The N application rates shown are reduced by 80 kg ha^{-1} compared with ratoon rates (Table 1). Other assumptions are the same as those described in Table 1.

Region	Production assumption	Cane yield (t ha^{-1})	N fertiliser (kg ha^{-1})	NiLRI (kg N (t cane)$^{-1}$)	N surplus (kg ha^{-1})
Mossman, Mulgrave, Innisfail, Tully, Herbert, Bundaberg	Potential yield	144	60	0.42	−26.4
Mackay	Potential yield	156	70	0.45	−23.6
Burdekin	Potential yield	204	120	0.59	−2.4
Mossman, Mulgrave, Innisfail, Tully, Herbert, Bundaberg	Actual yield	96	60	0.63	2.4
Mackay	Actual yield	84	70	0.83	19.6
Burdekin	Actual yield	138	120	0.87	37.2

from a preceding fallow nor a reduction in N application rates, NiLRI reference points will be the same as those of ratoon crops (Table 1). Thus, a NiLRI value of 1.3 provides a reference point for very high crop production (i.e. potential) being obtained with the application of the 6ES N guideline rates and 1.7 for average yielding crops.

3.4. NiLRI classes

The NiLRI reference points provide the basis for defining the water quality risk classes needed for the Paddock-to-Reef program. The Paddock-to-Reef water quality risk framework started with four classes; A, B, C and D (McCosker and Northey, 2015). Additional classes were subsequently added as it became apparent that "finer resolution" was needed in differentiating water quality risk. To provide this level of resolution in a new water quality risk framework we develop seven risk classes, which require defining six NiLRI values to be the boundaries between the classes. The number of boundaries is greater than the number of reference points developed above, so we use the reference points as a basis for some class boundaries and interpolate between them to derive the desired number of boundaries.

3.4.1. Ratoon crops

For ratoon crops, we propose the following NiLRI classes (Table 3) related to the reference points:

- Class 1, the lowest water quality risk, defined by NiLRI values < 1.0 kg N (t cane)$^{-1}$. While this is lower than the NiLRI associated with 6ES guidelines and potential yields (Table 1), there is evidence in experiments (Fig. 2a) that NiLRI values < 1.0 kg N (t cane)$^{-1}$ are achievable in ratoon crops. However, the conditions and/or management actions that result in these low NiLRI values are not currently known.
- Class 2 is defined by NiLRI values of 1.0–1.2 kg N (t cane)$^{-1}$ and aligns with the concepts of farmers applying N at 6ES guideline rates and achieving regional potential yields. Conceptually this class represents the "best" production system *with current technology*; that is achieving potential yields with industry N fertiliser guidelines (Table 3). The caveat "with current technology" is added to indicate that technological advances such as enhanced efficiency fertilisers (Verburg et al., 2022), seasonal climate forecast-based management (Biggs et al., 2021) and/or new varieties may improve the relationship between cane yield and N fertiliser applications, and hence reduce NiLRI and water quality risk.
- Class 4 is defined by NiLRI values of 1.4–1.7 kg N (t cane)$^{-1}$ and aligns with current common practice, i.e. achieving average yields with 6ES guideline N applications. This class conceptually represents the current average production system with current technology.

Table 3
Seven classes of water quality risk defined by values of the Nitrogen Loss Reduction Index (NiLRI) for sugarcane ratoon crops and the agronomic rationale for the boundary between classes. For some classes there is no agronomic rationale and the class have been defined to give an approximately linear differentiation between classes.

Class	NiLRI values (kg N (t cane)$^{-1}$)	Rationale for class boundaries
1	<1.0	Boundary of what is currently achievable
2	1.0–1.2	Potential yields with industry N fertiliser guidelines and current technology
3	1.2–1.4	*Near-linear differentiation between adjoining classes*
4	1.4–1.7	Average yields with industry N fertiliser guidelines
5	1.7–2.0	Crop growth and/or N uptake limited and *near-linear differentiation between classes*
6	2.0–2.3	Crop growth and/or N uptake limited and *near-linear differentiation between classes*
7	>2.3	Crop growth and/or N uptake limited and *near-linear differentiation between classes*

Boundaries for Class 3 have been set to provide a near linear grade in NiLRI values between Classes 2 and 4 (Table 3).

NiLRI values > 1.7 kg N (t cane)$^{-1}$, i.e. the upper boundary of Class 4, occur in experiments (Fig. 2a) and could arise in commercial farming for many reasons. One might be yields being limited by issues such as sub-optimal management of irrigation, as hypothesised above to be occurring at Mackay and discussed below, or by poor supply of other nutrients without a corresponding reduction in N application rate. Other reasons could be where N uptake by the crop is limited or N losses to the environment are high, and so N fertiliser applications need to be high to maximise yields in these situations. Thus, additional NiLRI classes are required. We have defined Classes 5, 6 and 7 to give a near linear extrapolation in the class boundary values (Table 3). The NiLRI values defining these three classes represent increasing degrees of limitation to crop growth and/or crop N uptake.

3.4.2. Plant crops

For plant crops, we propose the following NiLRI classes (Table 4) related to the reference points:

- Class 1, the lowest water quality risk, is defined by NiLRI values < 0.5 kg N (t cane)$^{-1}$. NiLRI values for this class represent plant crops following a legume fallow, achieving potential yields with N applications reduced by more than 80 kg ha^{-1} relative to ratoon crops (Table 2). We discussed above that an 80 kg ha^{-1} reduction in N was conservative. So this class characterises a situation where, for example, farmers are confident they have legume fallow crops with high biomass and considerably reduce N applications rates relative those for to ratoon crops. There is evidence in experiments (Fig. 2b) that NiLRI values < 0.5 kg N (t cane)$^{-1}$ occur in plant crops.
- Class 2 is defined by NiLRI values of 0.5–0.7 kg N (t cane)$^{-1}$, corresponding to plant crops following a legume fallow achieving potential yields with more conservative reductions in N applications than for Class 1, i.e. approximately 80 kg ha^{-1} less than ratoon crops.
- Class 3 is defined by NiLRI values of 0.7–1.0 kg N (t cane)$^{-1}$ and aligns with the concept of farmers achieving average yields with N applications 80 kg ha^{-1} lower than ratoon crops.

Table 4
Seven classes of water quality risk defined by values of the Nitrogen Loss Reduction Index (NiLRI) for sugarcane plant crops, and the agronomic rationale for the boundary between classes (i.e. the conditions prior to the plant crop, and assumptions about yields achieved and reduction in N fertiliser applications relative to ratoon crops). For some classes there is no agronomic rationale and the class have been defined to give an approximately differentiation between adjacent classes.

Class	NiLRI values (kg N (t cane)$^{-1}$)	Rationale for class boundaries		
		Condition prior to the crop	Yield equivalent to	Reduction in N fertiliser (kg ha^{-1})
1	<0.5	Green manure legume fallow	120% of ratoon crop potential yields	>80
2	0.5–0.7	Green manure legume fallow	120% of ratoon crop potential yields	80
3	0.7–1.0	Green manure legume fallow	Average yields of ratoons	80
4	1.0–1.3	Plough out/ Replant	Potential yields of ratoon crops	0
5	1.3–1.7	*Near-linear differentiation between adjoining classes*		
6	1.7–2.1	Plough out/ Replant	Average yields of ratoon crops	0
7	>2.1	*Near-linear differentiation between adjoining classes*		

- Class 4 is defined by NiLRI values of 1.0–1.3 kg N (t cane)$^{-1}$ and aligns with plough-out-replant crops achieving potential yields with N applications at 6ES N guidelines.
- Class 6 is defined by NiLRI values of 1.7–2.1 kg N (t cane)$^{-1}$ and aligns with average yielding plough-out-replant crops with N applications as per 6ES guidelines.
- Class 7 represents a situation where plant crop yield and/or N uptake is lower than Class 6. The boundaries defining Classes 5 and 7 have been set to provide a near linear grade in NiLRI values between water quality risk classes.

4. Water quality risk in sugarcane production

Information on the practices implemented on commercial sugarcane farms, as well as N fertiliser application rates and yield expectations, is obtained for the Paddock-to-Reef program through ongoing surveying of farmers participating in improved management programs (McCosker and Northey, 2015; Australian and Queensland Governments, no date (b)). The survey responses allow us to calculate NiLRI values for the crops surveyed and see how these compare with the seven NiLRI classes. Importantly, the survey data also (1) allow us to examine some assumptions made in defining the different NiLRI classes, and (2) provide potential insights into the practices associated with the NiLRI values and hence ways to reduce water quality risk.

4.1. NiLRI values in commercial cropping

4.1.1. Survey data

Data on farmers' crop management practices came from surveys conducted from 2016 to 2019 of practices over 170,177 ha of sugarcane production (Appendix 3). This area equates to 53% of the area planted to sugarcane in GBR catchments. We analysed responses to the 12 questions listed in Table 5. The survey data also included information on farmers' crop yield expectations, usual N fertiliser application rates and, for ratoon crops, how many times the crop had been harvested.

4.1.2. Yield expectations

One of the survey questions (6a, Table 5) asked farmers to report their yield expectations. There are a number of factors that may result in farmers' yield expectations being higher than the yields actually

Table 5
Selected questions asked of sugarcane farmers in surveys to quantify agricultural land management practice adoption for the Paddock-to-Reef Program (Australian and Queensland governments, n.d.(b)). The abbreviated version of the questions is used in to communicate results of the association between practices and survey responses (Section 4.2). Questions 6a and 6b are supplementary questions from which NiLRI values were calculated. For ratoon crops, information was also recorded on how many times the crop has been harvested.

No.	Question	Abbreviation
1	Do you normally use a green cane trash blanket?	Green cane trash blanket
2	Which best describes how machinery traffic is managed on your farm?	Machinery traffic
3	What is your current row width?	Row width
4	Which best describes your normal fallow management?	Fallow management
5	How do you normally prepare land for planting of cane?	Preparation for planting
6	Which best describes how you calculate your N fertiliser rate?	Calculation of Fert. N rate
6a	*What cane yield (tonnes cane per hectare) do you expect your farm will produce in a moderate- good season without any major problems (like cyclones and flooding)?*	NA
6b	*What is the nitrogen fertiliser rate that you generally apply under normal conditions?*	NA
7	Which best describes the placement of your N fertiliser?	Fertiliser placement
8	What % of your farm do you apply mill mud/ash[a] to each year	Prop. area of millmud/ash
9	At what rate do you apply mill mud or mud/ash?	Millmud application rate
10	Which best describes how you apply residual herbicides? (assume all are as per label requirements)	Residual herbicides
11	Which best describes how you use residuals herbicides in ratoons? (Assumption that all are as per label requirements)	Residuals in ratoon crops
12	Which best describes how you deal with rainfall runoff?	Rainfall runoff

[a] Mill mud/ash is a by-product of the purification process for extracting sugar from sugarcane during the milling process. It is commonly applied to sugarcane fields as a means of disposal. There can be considerable qualities of nutrients, including nitrogen applied to fields in this process.

achieved (Thorburn et al., 2011) which would cause NiLRI values calculated from the survey data to be lower than actually achieved. Thus, it is useful to check whether farmers' yield expectations were plausible. Farmers' actual yields ae not publicly available. In the absence of those data, we compared the average of the farmers' expected yields in a region to historical yields in that region obtained from industry statistics (Appendix 1). We also used the responses to examine assumptions about the relative differences between plant and ratoon crop yields made in calculating reference values for NiLRI classes (Section 3.2.2).

The range in farmers' ratoon crop yield expectations overlapped with the range in regional yields (Fig. 3). Median ratoon crop yield expectations fell within the 25th to 75th percentile range of regional yields (i.e. the width of the "box" in Fig. 3) for the majority of regions, except for the Bundaberg, Herbert, Innisfail and Mackay regions, where they were higher than the 75th percentiles. In these regions, the 25th to 75th percentile ranges of regional yields (4–13 t ha^{-1}) were smaller than most other regions, possibly because the data came from a small number of years. Thus, the data may represent an underestimation of the real variability in yields which is shown in the farmers' expectations. The 25th to 75th percentile range of regional yields was also small in the Burdekin region. This is because the plentiful supply of irrigation water in the region reduces the impact of climate variability on interannual yield variability.

Median plant crop yield expectations were greater than the 75th percentile of regional yields for all regions except for the Mulgrave (Fig. 3). The higher plant crop yield expectations are to be expected

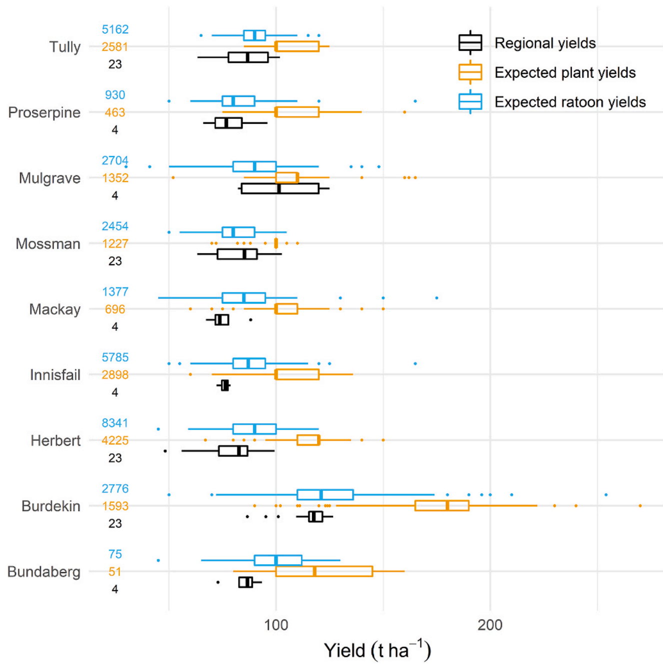

Fig. 3. Box plots of farmers' sugarcane yield expectations from responses to management practice surveys (Section 4.1.1). Plant and ratoon crops are differentiated. The numbers shown on the left are the number of survey responses for that crop class in a region. Also shown are box plots of annual average yields achieved in the regions (data sources given in Appendix 1). For these data, numbers on the left are the number of years prior to 2019 for which data was obtained. Note, ratoon and plant crops are not differentiated in the regional yield data.

because the regional yields are averaged across both ratoon and plant crops in a region, and there is a considerably greater area of ratoon crops.

Importantly, farmers' yield expectations for plant crops were 22% (20 t ha^{-1}) higher than for ratoon crops (Fig. 3). This increase matches well the 20% yield increase we assumed for deriving NiLRI reference points for plant crops following a fallow (Section 3.2.2).

4.1.3. *NiLRI values derived from survey data*

For both ratoon (Fig. 4a) and plant (Fig. 4b) crops the NiLRI values calculated from the survey responses spanned all seven NiLRI classes, confirming the relevance of the classes to Australian sugarcane production. For both crop classes, >40% of the farmers' values were in Class

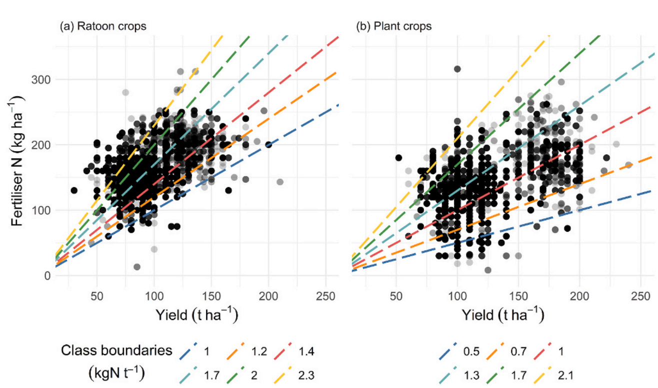

Fig. 4. Relationship between N fertiliser applications and yields for (a) ratoon and (b) plant crops recorded in the farmer survey responses (questions 6a and 6 b, Table 5). The ratio of N applications and yields define the NiLRI value. The dashed lines show the boundaries of the seven NiLRI classes described in Table 3 (ratoon crops) and 4 (plant crops).

4, with 15–25% in Classes 3 and 5 (Table 6). The concentration of values in these classes is expected and they represent near average production and N management (Tables 3 and 4).

4.2. *Practices associated with NiLRI classes*

NiLRI classes are defined by N fertiliser application rates and crop yields. However, while those two attributes quantitatively define NiLRI there are a range of management practices that influence sugarcane yield and the efficiency with which the crop can acquire and use N (Bell and Garside, 2014). The Paddock-to-Reef surveys contain a wide range of questions about general farm management practices (Table 5). In this section we investigate associations between the responses to those survey questions and the NiLRI. We used a supervised machine learning technique (i.e. classification random forest model) to identify those associations. As well as the questions asked in the surveys about management practices, we included additional information in the analysis, such as the region in which the farm was located, whether the ratoon crop was harvested late in the season and whether the ratoon crop had previously been harvested four or more times.

4.2.1. *Methods – machine learning analysis*

Classification random forest models (Breiman, 2001) were used for predicting a categorical response variable, in this case the NiLRI classes. The random forest model fits an ensemble of decision trees with each tree consisting of recursive decisions splitting the data into two groups. At each split the model attempts to minimise variability within groups and maximise variability between groups. The decision splits are based on the values of the supplied predictors (i.e. supervised learning). We ranked the importance of the predictors (i.e. variable importance) based on the increase in error when the predictor is randomly excluded during the generation of the trees (i.e. out-of-bag (OOB) error rate). This error is estimated automatically within the "randomForest" package (Liaw and Wiener, 2002) within the R statistical programming environment (R Core Team, 2020).

For this analysis, a random selection of 75% of the data was used to train the model with the remaining data used in the model assessment. Due to the highly imbalanced representation of NiLRI classes the data used for training was firstly up-sampled, with replacement, to ensure equal representation of each class. The analysis was performed using 1000 trees and 11 predictors (Table 5) excluding questions related to fertiliser amount and yield expectations as these define NiLRI values. Model performance was assessed based on the remaining data (25%) after the training data was removed. Prediction accuracy was calculated based on the proportion of correct classifications for each class (presented as a stacked bar chart) and over the whole test dataset.

The analysis was undertaken on data from all regions. Ratoon crops and plant crops were analysed separately.

4.2.2. *Results*

Overall, the random forest models accurately predicted the NiLRI class 89.6% and 93.0% of the time for ratoon and plant crops, respectively. The random forest model categorised the ratoon crop survey data with more than 90% accuracy in all NiLRI classes, except Class 4 which

Table 6
The proportion (%) of responses to the Paddock-to-Reef survey that fell into each of the seven water quality risk classes (shown in Fig. 4).

Class	Ratoon	Plant
1 (Lowest risk)	1.5	3.5
2	3.6	4.3
3	15.3	24.3
4	43.1	40.5
5	24.9	24.5
6	7.1	2.1
7 (Highest risk)	4.5	0.8

had an accuracy of 87% (Fig. 5a). Plant crop data was categorised with more than 90% accuracy (Fig. 5b).

The relative importance of the responses to questions (Table 5) in determining NiLRI classes differed between ratoon (Fig. 6a) and plant (Fig. 6b) crops. However, three of the four most influential questions were the same for each crop class, i.e. the “Region” in which the land parcel was located or questions on fallows (type or management) and “Preparation of the land for planting”. Other influential questions related to management of mill mud (questions 8 and 9), use of residual herbicides in ratoon crops (questions 10 or 11) or management of rainfall runoff (question 12). “Fallow type” was the most influential question for plant crops but not influential for ratoons crops. “Fertiliser placement” was also one of the more influential question for ratoon crops but the least influential for plant crops.

Median NiLRI values generally varied between the different answers for the highly influential questions by 0.1–0.4 kg N (t cane)$^{-1}$. With ratoon crops for example, the two responses to the “Crop age” question (Fig. 6a) had median NiLRI values of 1.0 and 1.2 kg N (t cane)$^{-1}$ for crops that had been harvested less or more than four times, respectively. For the “Region” question, NiLRI values in the Mackay region were approximately 0.4 kg N (t cane)$^{-1}$ higher than in the other regions. It is interesting that the questions “Fallow management” and “Preparation of land for planting” refer to management of the land **prior** to establishment of a plant crop, yet these questions influenced ratoon crop NiLRI values.

With plant crops (Fig. 6b), farmers in catchments in the Mackay region had median NiLRI approximately 0.3 kg N (t cane)$^{-1}$ higher than in other regions. For the “Fallow type” question, median NiLRI values were lower in plant crops preceded by a legume fallow (1.1 kg N (t cane)$^{-1}$) than a bare fallow (1.2 kg N (t cane)$^{-1}$) or no fallow (i.e. plough-out/replant crops, 1.3 kg N (t cane)$^{-1}$).

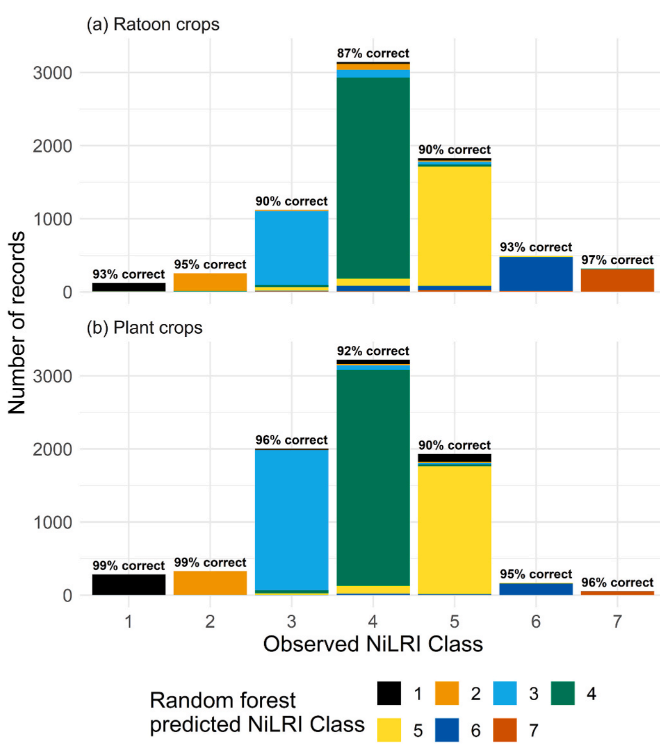

Fig. 5. Accuracy of categorisation by the random forest model of farmers’ responses to survey questions (Table 5) into NiLRI Classes for (a) ratoon and (b) plant crops. The number of erroneous classifications (e.g. a field with NiLRI of Class 1 being classified as Class 4)is also shown.

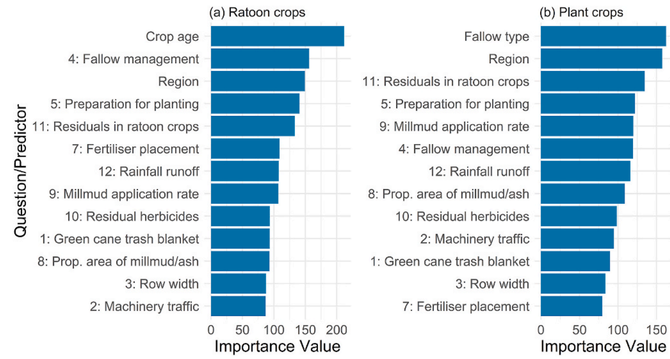

Fig. 6. Relative importance of the different crop management practices for determining NiLRI classes for (a) ratoon and (b) plant crops. The “Question/Predictor” data came from a survey of 1633 sugarcane farmers (details given in Table 5 and Appendix 3). In the surveys, information was also collected about the region (Region) in which the farm was located, and whether a ratoon crop had been harvested four or more times (Crop age).

5. Discussion

Improving farmer’s management of N fertiliser is an important part of reducing water quality pressures on many ecosystems (Schlesinger, 2009; Zhang et al., 2015; Martínez-Dalmau et al., 2021). This is true for sugarcane cropping in north eastern Australia, which is the main source of dissolved N discharges to Great Barrier Reef (GBR) ecosystems (Kroon et al., 2016; State of Queensland, 2018). Having a widely applicable and practical method of characterising the water quality risk of farmers’ management practices allows farmers and others to understand the water quality risk of their management practices (McCosker and Northey, 2015). It will also encourage farmers and their advisors to engage with ways to reduce that risk. In this study we developed a readily calculated metric, NiLRI, to assess the risk of N losses from sugarcane crops. While NiLRI is related to the commonly used metrics N surplus and NUE, it has some advantages over both. NiLRI is directly related to N losses from cropped fields, whereas NUE is inversely related. Thus, communication of water quality risk to farmers will be easier with NiLRI. Compared with N surpluses, calculating NiLRI values requires fewer assumptions and the NiLRI classes developed in this case study were more generally applicable across regions than N surplus values. For example, NiLRI values for two production scenarios assumed in the study were reasonably consistent between regions (Tables 1 and 2). In contrast, N surplus values for these assumptions varied by approximately 18% between regions for ratoon crops (Table 1) and approximately 100% for plant crops (Table 2). The consistency of NiLRI class definition across sugarcane production regions in GBR catchments will facilitate widespread scaling of the concept.

What do NiLRI values of commercial sugarcane production tell us about water quality risks in GBR catchments? NiLRI values determined from the surveys of management practices spanned all seven classes (Fig. 4), with 10–12% of the land surveyed in the two highest risk classes (Table 6). Efforts to reduce water quantity risk would be well targeted at these areas. This result then raises the question; what can be done to reduce water quality risk? The NiLRI metric is the ratio of N fertiliser applied to cane yield, suggesting the way to reduce NiLRI and water quality risk is to reduce N fertiliser applications and/or increase cane yields. Certainly, where there are opportunities to reduce N application rates without reducing yields (Thorburn et al., 2011; Webster et al., 2012; Rohde et al., 2013a,b) they should be taken. However, a singular focus on N rates is too simple. Indeed, such a simplistic interpretation is reducing industry acceptance of the practice-based water quality risk framework currently used in GBR catchments (Canegrowers, 2020). Alternatively, if it was easy or convenient for farmers to implement practices to increase yields, they most likely would have done so. The complexity of the situation is illustrated by the association between NiLRI values and farm management practices (Fig. 6). Most influential practices seemingly have little direct impact on either N management or crop yields. Thus, the results of this study suggest that reducing NiLRI will be helped by implementing a range of practices to improve soil health allowing more efficient uptake of N from the soils and reducing limitations to crop growth (Bell and Moody, 2014). As indicated by the results in Fig. 6, these practices include appropriate fallow management (breaking monocultures), and reducing tillage and compaction (Bell and Garside, 2014; Garside and Bell, 2011; Garside et al., 2009).

Another practice that will influence NiLRI values in sugarcane production is irrigation. Good irrigation management increases crop growth and vigour, potentially increasing uptake of N while avoiding increasing N leaching (Holden and McGuire, 2014). The potential impact of irrigation management on NiLRI values is illustrated by the development of the NiLRI reference points (i.e. independent benchmarks) for ratoon crops. The NiLRI reference point for average yielding crops in the Mackay region (2.14 kg N (t cane)$^{-1}$, Table 1) was higher than for other regions (1.75 kg N (t cane)$^{-1}$) because average yields were low relative to potential yields in Mackay than other regions. However, if average yields were 15 t cane ha^{-1} higher in Mackay the NiLRI reference point would be similar to other regions. It is possible this yield increase could be achieved by more effective and timelier use of irrigation water, for example applying relatively more irrigation during early crop growth stages (Hardie et al., 2000) and/or applying an additional 1 to 1.5. ML ha^{-1} of irrigation water to crops in the region (Holden and McGuire, 2014). Mackay farmers use <40% of their available irrigation water supplies (Sunwater, 2020), so between these two changes to irrigation management there seems to be scope to increase yields and decrease NiLRI values in the region. This discussion of the potential impact of improved irrigation on NiLRI values in Mackay also illustrates there is likely to be value in considering the regionally-specific factors that determine NiLRI values, going beyond the analysis of data aggregated across all regions reported here (Fig. 6).

Finally, it is worth considering the relevance of this study for other contexts, both other places where N fertiliser management poses water quality risks or concern over greenhouse gas emissions. N fertiliser application is a significant contributor to hypoxia in the aquatic and marine ecosystems in many areas other than GBR catchments (Howarth, 2008; Fowler et al., 2013; Martínez-Dalmau et al., 2021) and the NiLRI metric may be a useful risk indicator in these areas. Two examples are Norway (Hellsten et al., 2019) and the USA mid-west (Jones et al., 2018). In both countries, there are opportunities to reduce N losses from cropping through the adoption of improved management practices, such as sowing cover crops, splitting N fertiliser applications and refining N application rates. Providing information to farmers on the water quality risk benefits of these and other crop management practices could encourage voluntary adoption of the practices (Hellsten et al., 2019; Marks and Boerngen, 2019). Moreover, there are similarities between N fertiliser management of sugarcane and corn crops in the USA mid-west, including large temporal variations in optimum N rates and a poor correlation between optimum N rates and yields (Morris et al., 2018; Puntel et al., 2018). Determining NiLRI values of corn crops and the N fertiliser applications, yields or other factors that drive those values may provide benchmarks of water quality risk and a better insight into how water quality risk may be reduced without increasing the risk of yield losses. In terms of other environmental impacts of N fertiliser management, a critical impact of N fertiliser management is exacerbating emissions of the greenhouse gas nitrous oxide. The NiLRI concept is likely to be applicable to assessing risks of nitrous oxide emissions because, like dissolved inorganic N discharges, nitrous oxide emissions increase as N fertiliser applications increase even though crop yields do not (Thorburn et al., 2010; Shcherbak et al., 2014).

6. Conclusion

The management of N in agriculture is a concern in many regions because of hypoxia in the aquatic and marine ecosystems. Evaluating the success of policies for improving N management is difficult, but can be made easier through the use of straightforward methods to rapidly assess the likely outcomes of different management practices promoted by the policies. The simple NiLRI metric developed in this study overcomes problems with some common methods, such as cost, difficulty in scaling and/or communication with stakeholders. The NiLRI metric is calculated from readily obtained information, is directly related to N discharges from cropping systems and easily communicated to farmers and policy makers. This simplicity with which NiLRI values can be derived means it is possible to collect and analyse NiLRI values from large numbers of fields. In this study, these analyses identified links between NiLRI and unexpected crop management practices providing new insights into how crop management could be changed to reduce water quality impacts.

While NiLRI was developed in the context of assessing water quality risks of sugarcane cropping in Great Barrier Reef catchments, the metric could be developed for other crops and other locations. The application of the NiLRI metric and analytical methods in these situations may yield insights into new ways to improve crop management as was found in this study. The metric could be extended to include N from non-fertiliser sources, such as manure, as was illustrated in this study by the inclusion of N input to cropping systems from legumes. Likewise, it can likely be extended to the problem of nitrous oxide emissions from agriculture. However, the simplicity of the NiLRI metric also likely imposes limitations on applications of the concept. It implicitly operates at the field scale, so application at the farm scale in situations where there are transfers of N across the farm as happens in animal production systems will be difficult. Application to nutrients such as phosphorus, where stores in soils can take decades to reach equilibrium, will also be problematic. However, where these management practices or soil process are not important the NiLRI metric has the potential to facilitate evaluation of N management policy and regulations, and inform how crop management could be changed to reduce water quality and other environmental impacts.

Author statement

Peter Thorburn: Conceptualization; Methodology; Data analysis; Writing, original draft, review & editing. **Jody Biggs**: Data analysis; Visualisation; Writing, original draft, review & editing. **Kevin McCosker**: Conceptualization; Writing, review & editing. **Adam Northey**: Data curation; Conceptualization.

Declaration of competing interest

The authors have no competing interests to declare.

Data availability

The authors do not have permission to share data.

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Appendices.

1. Data on regional average sugarcane yields

Each year the Australian sugar industry publishes data on regional sugarcane. These data are reported by industry bodies such as Canegrowers Australia (e.g. at http://www.canegrowers.com.au/page/about/publications/canegrowers-annual-report-2018-19/, accessed December 21, 2021) and the Australian Sugar Milling Council (e.g. at https://asmc.com.au/policy-advocacy/sugar-industry-overview/statistics/, accessed December 21, 2021). Data were also sourced from research studies (e.g., Shcherbak et al. (2014) and Biggs et al. (2021)).

2. Derivation of optimum N fertiliser application rates in Fig. 2

Data were collated from field experiments where sugarcane yield had been measured at different rates of applied N fertiliser (e.g. Fig. 1). Sources of the data are listed by Thorburn et al. (2018). The experiments had been conducted in the major sugarcane producing regions in north eastern Australia, approximately bounded by the cities of Logan (latitude 27.73^{o}S) and Cairns (latitude 18.83^{o}S). The experiments had at least four N rate treatments. The collation resulted in 238 N responses for ratoon crops and 63 for plant crops.

For each experiment, the change in cane yield with increasing N application rates (i.e. the N response curve) was emulated by a second degree polynomial equation fitted to N response data. A range of other equations were tested as emulators (following Thorburn et al., 2017), but they had little effect on the results (data not shown).

The optimum N rate of the N response curves was defined as the N rate that gave 95% of maximum yield, a definition commonly used in the Australian sugar industry (Schroeder et al., 2014). The value of the optimum N rate was derived from the emulated response curve and the yield at the optimum N rate calculated. Thus, each experimental N response curve is represented in Fig. 2 as a single point, being the value of an optimum N rate and yield at the optimum N rate.

3. Management practice surveys

There are a range government funded programs available to sugarcane farmers in GBR catchments to facilitate adoption of new management practices to improve the quality of water leaving their farms. The change in management practices of farmers participating in these programs are evaluated by surveying farmers about their practices both before and after their participation in the programs (McCosker and Northey, 2015; Australian and Queensland Governments, no date(b)) with questions designed to elicit information relevant to assessing change in practices to improve water quality. Completion of farm management surveys is a condition of participation in the programs. The surveys commenced in 2013 and contain 17 questions on their crop management practices. From 2016 the survey included more general information on farmers' crop yield expectations (question 6a, Table 5), usual N fertiliser application rates (question 6 b) and, for ratoon crops, how many times the crop has been harvested.

The surveys were conducted as one-to-one, semi-structured interviews between farmers and staff delivering the government funded programs, who are typically professional extension officers or farm management consultants. Survey responses describe the farm management practices implemented on "land parcels", not on a per-farm or per-farmer basis. Land parcels may represent the entire farm, or individual fields on a farm (e.g. where a farmer may be experimenting with alternative fertiliser rates). The spatial location and area of the land parcel is accurately recorded as part of program participation, and a survey response represents a unique parcel of land.

This study used data from 1633 surveys conducted from July 2016 to June 2019 of the practices implemented in each land parcel prior to participation in a practice change program. Prior to analysis in this study, the data were checked and corrected for possible spatial overlaps in land parcels due to farmer's participation in multiple programs operating in some regions during this period. The total area of the land parcels covered in the surveys was 170,177 ha. The specific spatial locations and other personal identity attributes of the survey data, except for the region in which the land parcel was located, were removed to anonymise the data prior to inclusion in this study.

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