

Research article

Trends in fertiliser use and efficiency in the Great Barrier Reef catchment area

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ABSTRACT

Time series data of annual fertiliser application in river basins provide a foundational record of crop management practices and environmental change. Here we produce an annual time series of synthetic nitrogen (N) and phosphorus (P) fertiliser application for the river basins of the Great Barrier Reef (GBR) catchment area of north-eastern Australia spanning from 1910 to 2024. We draw on statistical data of basin-scale land use for various crop types coupled with known application rates to develop the time series, accounting for the uncertainties in both crop area and application rates. The compilation shows that N and P application has declined across four of the six natural resource management regions over the past one to two decades, however, there is considerable variability at the basin-scale, particularly in the timing of peak fertiliser application. This variability reflects changes in land use including shifts in crop types and/or cropped areas, as well as reductions in fertiliser application rates. We also show that mill mud/ash application to sugarcane crops provides extra plant-available N and P that should be incorporated into farm-scale nutrient budgets. Finally, we evaluate the long-term trends in N use efficiency in sugarcane, the dominant crop in the GBR catchment area, and reveal that the industry has improved markedly over the past one to two decades while maintaining consistent yields. These data contribute an important line of evidence for evaluating long-term trends in water quality and provide insights into the changing environmental footprint of croplands within the GBR catchment area.

1. Introduction

Twentieth Century agriculture was revolutionised with the increased manufacture of synthetic nitrogen (N) fertiliser, the invention of pesticides, improved field machinery and the development of hardy and productive crop varieties (Smil, 2001). These improvements allowed farmers to feed the growing population without the need to greatly increase the area of agricultural land (Smil, 2001; Kuhn, 2026). In particular, the Haber-Bosch process, used to produce ammonia and urea fertilisers, was fundamental to ensure an abundant, secure and affordable N supply (Galloway and Cowling, 2002; Galloway et al., 2004). Unfortunately, increased N and phosphorus (P) fertiliser usage has led to increased losses to the environment resulting in polluted receiving waterways and causing widespread environmental harm (Green et al., 2004; Beman et al., 2005; Bouwman et al., 2005; Boyer et al., 2006;

Van Meter et al., 2018; Marion et al., 2021; Grinham et al., 2024). These impacts have presented challenges for the agricultural sector to improve N and P use efficiency and reduce off-paddock fertiliser losses.

The Great Barrier Reef catchment area (GBRCA) of north-eastern Australia has been under particular scrutiny, as riverine N and P loads have increased several-fold across many of the 35 river basins since the arrival of Europeans c. 1850 (Kroon et al., 2012; McCloskey et al., 2017, 2021). Increased riverine nutrient loads have been linked to negative effects on the adjacent coastal and marine ecosystems within the inshore GBR (Fabricius et al., 2005; Brodie et al., 2012; Uthicke et al., 2012; Thompson et al., 2014; Diaz-Pulido et al., 2024 and references therein) and potentially further offshore (Fabricius et al., 2010; Babcock et al., 2016; Brodie et al., 2017). As a result, governments have focussed on encouraging farmers to adopt improved management practices to reduce N and P paddock losses and have also regulated N application

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rates for certain crops (Eberhard et al., 2021). These interventions form part of the Reef Water Quality Protection Plan which was launched in 2003 (Carroll et al., 2012) and is now known as the "Reef 2050 Water Quality Improvement Plan" (Reef Plan, 2024).

Broad spatial scale studies have evaluated N budgets for Australia (e.g.; Angus and Grace, 2017; Kraak et al., 2024) and the N amount applied for the whole GBRCA (Kroon et al., 2016), while at the finer paddock spatial scale there has been considerable research on fertiliser application, management and efficiency (Thorburn and Wilkinson, 2013; Armour et al., 2022; Thorburn et al., 2024). The "six easy steps" method for fertiliser application in sugarcane crops was developed to improve practices (Schroeder et al., 2010, 2018; Calcino et al., 2018) and was subsequently regulated across the GBRCA (Eberhard et al., 2021; Hasan et al., 2021; State of Queensland, 2022). Despite the strong focus on fertiliser management to reduce nutrient loads to the GBR, there is limited knowledge of how the total N and P quantities applied at a river basin scale have changed over time, whether application rates have reduced and if nutrient use efficiency has increased under improved management practices. These measurements require either accurate data of annual areas of fertilised land use within a basin coupled with average N and P application rates, or detailed annual fertiliser sales/-application data for each basin. Unfortunately, fertiliser sales data are not publicly available, and the data related to fertilised land use are nuanced by reporting districts that overlap multiple river basins as well as changing boundaries and reporting parameters over time (Lewis et al., 2021).

To date, the only study to compile synthetic N and P fertiliser application data for the river basins of the GBR was conducted by Jim Pulsford (Pulsford, 1996) who presented a time series from 1910 to 1990. Pulsford (1996) used the fertilised areas of five separate crop groupings (sugarcane, fruit, vegetables, field crops and pastures) reported by the Australian Bureau of Statistics (ABS) and integrated these with regional-scale annual industry fertiliser sales records to produce the basin-scale time series. The N and P contents of each fertiliser product were accounted for to produce the annual totals of synthetic N and P applied to each GBR basin (Pulsford, 1996). While there has been no recent compilation of synthetic N and P fertiliser application over the past 35 years, surveys of fertiliser application rates are gathered to inform the Dynamic SedNet model. The Dynamic SedNet model quantifies basin-scale nutrient load reductions as a result of management improvements (McCloskey et al., 2021), although the land use area and fertiliser application are benchmarked to a "baseline" year and do not reflect annual changes in total N and P application. An annual time series of the cropping areas for the river basins of the GBRCA has been compiled by Lewis et al. (2021) which accounts for the statistical districts which overlap river basins. A compilation of annual N and P fertiliser application at the river basin-scale is timely, providing an additional line of evidence to assess whether nutrient management has improved across the GBRCA.

The overarching aim of this contribution is to develop a foundational time series of N and P fertiliser use at the river basin scale, revealing critical insights into past fertiliser application and management practices, as well as providing guidance on future management. This aim is achieved in three steps: firstly, we compile land use specific ABS district data within the river basins of the GBRCA for seven crop groupings (sugarcane, fruit and nuts, bananas, vegetables, field crops, cotton and dairy pasture) for the years 1990 to 2024. Secondly, we compile available N and P fertiliser application rates for these crop groupings and, using the corresponding land use area data, calculate the amount of fertiliser (N and P) applied to each crop grouping within each GBR basin between 1991 and 2024. We apply uncertainty estimates, expressed as coefficients of variation, for both the cropped area and the corresponding N and P fertiliser application rates to derive uncertainty distributions for each of the time series. This contribution updates the Pulsford (1996) time series to provide synthetic fertiliser N and P amounts for the GBR river basins over the extended period 1910 to

2024. We also conduct a case study to examine the plant-available N and P from mill mud/ash and animal manure recycled within river basins and examine how this contributes to farm-scale N and P budgets. Finally, we use the N time series data for the dominant crop, sugarcane, and compile the annual sugarcane production data (tonnes harvested) to examine the yield and N use efficiency for this industry. This was done by examining the tonnes per hectare harvested (i.e. yield) and the kilograms of N per tonne of sugarcane harvested (i.e. efficiency), respectively. This new compilation produces valuable insights into the changes in N and P fertiliser application across the GBR river basins and highlights the remaining challenges for the agricultural sector in the GBRCA.

2. Background and methods

2.1. The Great Barrier Reef catchment area (GBRCA)

The 423,000 km² GBRCA of north-eastern Australia comprises numerous streams that discharge into the GBR lagoon. It consists of 35 separate major river basins and, for management purposes, six natural resource management (NRM) regions including Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary (Fig. 1). The climate, vegetation and land use across these 35 basins are highly variable and range from wet tropics rainforest to desert uplands and dryland savannah (Furnas, 2003; Lewis et al., 2021; Puignou Lopez et al., 2025). Around 72% of the catchment area is used for cattle grazing, 15% is conservation land while around 3.5% is used for cropping lands. Sugarcane (1% of the area) is the dominant crop grown in the GBRCA and is mostly confined to the coastal floodplains (Lewis et al., 2021). Despite this seemingly low proportional contribution in area, sugarcane contributes 42% of the total average annual load of dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonium) discharged to the GBR lagoon (McCloskey et al., 2021). Hence the sugarcane industry has been a key focus of government policy and scientific research to improve management practices and reduce DIN loads to the GBR.

2.2. The Pulsford compilation

The Pulsford (1996) 1910 to 1990 time series of N and P application for GBR river basins involved complex integration of industry sources and sales data for different fertiliser products. This included calculating the N and P amounts in each product, the ABS data for fertiliser application amounts (although no fine spatial scale statistical district data were available prior to 1971) and the ABS data for fertilised land use areas for the various crop groupings. Pulsford (1996) demonstrated that the ABS fertiliser application data produced much lower estimates than the corresponding fertiliser sales data and postulated that the ABS census data were underestimated. He concluded it was "highly likely that census figures, in terms of areas fertilised and tonnages used, became less accurate as the complexity of the tables on the [census] form increased" and "in more recent times, when direct comparisons can be made with fertiliser industry sales data for the same geographic area, considerable differences are apparent" (Pulsford, 1996 p. 7). In contrast, Pulsford (1996) contended that the ABS data for the fertilised cropping areas would be reasonably accurate as primary producers are acutely aware of their cropping area. This section of the census form is straight forward to document, is consistent over time, and has less potential for error. In any case, it can be assumed any errors made on census forms in cropping area would be consistent from year-to-year (i.e. low bias) and that changes in the areas fertilised likely reflect the major variations in nutrient usage better than changes in the fertiliser tonnages applied (Pulsford, 1996). Hence, Pulsford (1996) applied the area of land fertilised combined with sales data of fertiliser products (normalised for their N and P contents) to provide estimates of N and P usage for each local authority statistical district which was then allocated to a GBR basin. While Pulsford (1996) noted the nuances of allocating fertilised areas reported in the statistical districts to a specific GBR basin (see also Lewis et al., 2021), the

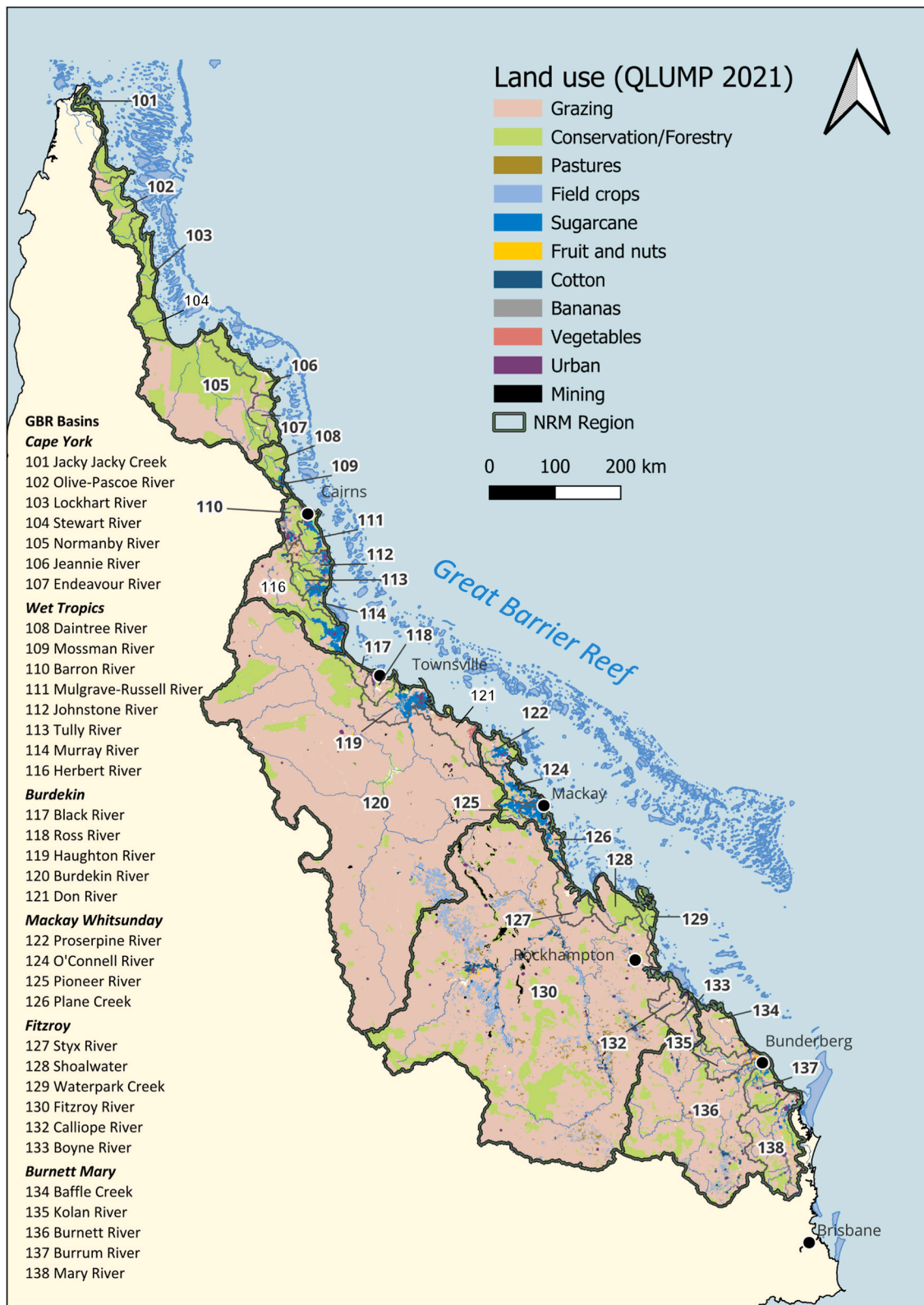


Fig. 1. The Great Barrier Reef catchment area showing the land use of the key crop groupings within the river basins and NRM regions (Data Source: QLUMP, 2021; <https://www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/qlump>).

sugarcane area for each basin at that time was used to calibrate the time series. At the end of the Pulsford (1996) time series in 1990, sugarcane accounted for 71% of the total N use and 55% of the total P use.

Overall, Pulsford's (1996) compilation provides a unique and valuable record that can be updated to examine longer-term fertiliser

application trends in the intensive cropping lands of the GBRCA. It cannot be independently validated due to the unavailability of fertiliser sales records – so its accuracy must therefore be implied – one test of this record can be made from known fertiliser application rates combined with the ABS data of area fertilised. Critically, Pulsford (1996) provided

the amount of N and P applied to each of five main crop groupings – sugarcane, fruit, vegetables, field crops, and pastures – for each basin in the last year (1990) of reporting. These data allow us to use the corresponding land use statistics (i.e. area fertilised) for each of these crop groupings to impute the specific crop N and P fertiliser rates applied for each basin in 1990.

2.3. Land use data compilation

We compiled additional ABS statistics to best capture the fertilised area for each of the main crop groupings applied by Pulsford (1996). Some of the measured parameters have changed over time and so alternative metrics needed to be collated. For example, the 1990 ABS statistics reported the “sugarcane area fertilised”, although this was not reported in the following years. The ABS statistics continued to report the areas of sugarcane cut for crushing (i.e. the main crop harvested for sugar production), sugarcane cut for plants (i.e. the billets harvested to plant for a new crop), sugarcane standover (i.e. the sugarcane not able to be harvested before the next growing season) and sugarcane newly planted (i.e. newly planted area) which are summed to represent the total sugarcane area. We compared these metrics with the sugarcane area fertilised metric in 1990 and found that the total area of sugarcane minus the sum of the sugarcane standover area and the newly planted sugarcane area were within $\pm 10\%$ (and mostly within $\pm 5\%$) for all basins. The newly planted sugarcane represents the area that was under fallow (i.e. unfertilised) in the previous season and the standover was also not fertilised in the year of reporting. There were a couple of years where this metric was not reported and the closest measure was “sugarcane cut for crushing” which was applied for those years (Supp. Table 1). Indeed, the sum of the sugarcane cut for crushing and sugarcane cut for plants metrics produce an identical result (to the fertilised sugarcane area metric) of which the cut for crushing metric represents the most dominant (generally $\geq 95\%$) area.

Both the fruit (all fruit excluding grapes area – and including nuts) and vegetable (vegetables for human consumption) metrics were stable over the entire 1990 to 2024 compilation period while the field crops (i.e. broadacre crops) were represented by the difference between the total cropping area and sum of the sugarcane, fruit, vegetable and cotton metrics (Supp. Table 1). We also compiled the total banana area metric and considered this separately to the fruit area. Bananas are an important crop for several basins of the Wet Tropics NRM region and banana specific fertiliser application rate data are available. Similarly, the cotton area was also compiled and considered separately from the field crops metric as it makes an important contribution with respect to N and P fertiliser application in the Fitzroy Basin and temporal N and P application rates are also available for this crop.

The fertilised pasture area was more difficult to capture in our analysis. From Pulsford's (1996) data, it was evident that fertiliser application to pastures was mostly linked to the dairy industry; however, the ABS do not report area of dairy land. We compiled the available ABS statistics to most closely represent the dairy area for each basin. This was done by compiling the ABS statistics for the total dairy cattle numbers. Proportional allocations of the dairy cattle numbers for each statistical district to river basins were informed by the numbers reported in each basin in 2006 (ABS, 2008) following the method of Lewis et al. (2021). The five basins with the highest dairy cattle numbers (>2000 head) coincided with the largest dairy areas reported by the Queensland Land Use Mapping Program (QLUMP) including the Mary, Johnstone, Burnett, Barron and Herbert (QLUMP, 2021). We used the reported 2021 QLUMP dairy areas for these five basins with the corresponding 2021 dairy cattle numbers to inform the stocking rates within each of these basins. This analysis revealed stocking rates of 5 dairy cows per hectare for the Mary Basin, 7 dairy cows per hectare for the Burnett Basin and 4 dairy cows per hectare for the Johnstone, Barron and Herbert Basins, which were then applied to calculate the dairy pasture area time series for these basins, respectively. For the remaining basins which had lower

dairy cattle numbers, 4 dairy cows per hectare were applied to inform their dairy pasture area with the exception of the Fitzroy and Burdekin basins where 7 dairy cows per hectare were applied to inform the dairy pasture area; the Burnett Basin stocking rate was used for these larger basins as this is a closer analogy. We note that Pulsford (1996) reported relatively high N application to pastures in the Mackay Whitsunday basins (Proserpine, O'Connell, Pioneer and Plane), although there are few dairy cattle in these basins. Hence, we were not able to replicate Pulsford's (1996) pasture fertiliser application for these basins in our analysis. The compiled land use area metrics used for each year are provided in Supp. Table 1.

The ABS, 2022 provide estimates of the uncertainties reported for their district cropping area data such as “relative standard error of 10% to less than 25% and should be used with caution”. However, no estimates of relative standard error were typically reported by the ABS for cropping areas that were mostly > 1000 ha. In these cases, the relative standard error ranges from 0% to 9.9% (i.e. within 10%); the driving factors for these error ranges are reflected by both the number and consistency/variability of the respondents within the ABS surveys (S. Geltner pers comm, 2026). The ABS data also represent a continuous, consistent and long-term resource that allows spatial and temporal trends to be evaluated. Based on this evidence, we have assigned uncertainties in the crop area groupings (Table 2).

2.4. Sugarcane production data compilation, and N fertiliser rate and N use efficiency calculations

We also compiled ABS production metrics for the sugarcane industry including the “cut for crushing” sugarcane area and the corresponding total tonnes of sugarcane harvested extending back to when they were collectively reported from 1945 (Statistics of the State of Queensland, 1945-1974; ABS, 2022). Together, these metrics provide a long-term time series of the sugarcane yield quantified in tonnes per hectare of harvested sugarcane. Furthermore, the sugarcane synthetic N fertiliser applied within each basin can be used with the corresponding sugarcane fertilised area and total tonnes harvested to calculate long-term time series of N fertiliser application rates (kilograms of N applied per hectare of sugarcane) and N use efficiency (i.e. kilograms of N per tonne of sugarcane), respectively for the sugarcane industry. As we didn't have the specific amount of the N fertiliser applied to sugarcane for each basin prior to 1990, we only used the basins – Daintree-Mossman (combined), Russell Mulgrave, Herbert, Haughton-Burdekin (combined), Proserpine, O'Connell-Pioneer (combined), Plane and Burrum – where the dominant proportion (i.e. > 80%) of N fertiliser applied can be attributed to the sugarcane industry to calculate this long-term N use efficiency. We calculated the proportions of the N fertiliser applied to sugarcane to the total N applied for each basin in 1990 as reported by Pulsford (1996). These proportions were then used along with the total N applied for each basin as reported by Pulsford (1996) to estimate the fertiliser N applied in sugarcane in the selected basins between 1945 and 1989. As of 2024, these basins represent 77% of the total sugarcane area across the GBRCA, and the respective basins capture 63% of the sugarcane in the Wet Tropics NRM region, 92% in the Burdekin NRM region, 100% in the Mackay Whitsunday NRM region and 29% in the Burnett Mary NRM region.

2.5. Allocations of statistical data to river basins and data infilling

The allocation of the compiled ABS statistics for each district to the GBR river basins was informed by spatial analysis drawing on the QLUMP crop areas (total cropping, sugarcane, banana, fruit and nuts, and vegetables) from the earliest (1999) and latest (2021) releases (QLUMP, 2021). In combination with the ABS statistical district boundaries over two separate reporting periods (i.e. local authority areas relevant for the 1945 to 2006 period and SA2 areas relevant for the 2011 to 2021 period) along with the river basin boundaries, we

Table 1

Fertiliser application rate sources for the crop groupings (Armour and Ford, 1996; Daniells, 1995; DPI&F, 2007; Fullelove et al., 1998; Gourley et al., 2012; Harper, 2014; Irvine-Brown et al., 2024a, 2024b; Jackson et al., 1997; King, 2021; Koci and Nelson, 2016; Leeks, 2019; Meurant et al., 1999; Newett, 2017; Newett et al., 2018; O'Hare et al., 2004; Olsen, 1992; Owen-Turner et al., 1997; Ross et al., 2000; Roth, 2010; Roth Rural, 2017; Stork et al., 2009; Wright et al., 1997, 2005).

Metric	Sugarcane	Fruit and nuts (minus bananas)	Bananas	Vegetables	Field crops (minus cotton)	Cotton	Pastures
Key basins (> 150 t N)	Daintree, Mossman, Barron, Russell Mulgrave, Johnstone, Tully, Murray, Herbert, Haughton, Burdekin, Don, Proserpine, O'Connell, Pioneer, Plane, Kolan, Burnett, Burrum, Mary	Barron, Russell Mulgrave, Murray, Waterpark, Fitzroy, Baffle, Kolan, Burnett, Burrum, Mary	Cape York, Barron, Russell Mulgrave, Johnstone, Tully	Haughton, Don, Kolan, Burnett, Burrum	Barron, Haughton, Burdekin, Fitzroy, Burnett, Mary	Burdekin, Fitzroy, Burnett	Barron, Johnstone, Herbert, Burnett, Mary
Range N rate used 1991-1995	167 to 270 kg.ha ⁻¹	20 to 400 kg.ha ⁻¹	520 kg.ha ⁻¹	40 to 180 kg.ha ⁻¹	0 to 90 kg.ha ⁻¹	110 to 165 kg.ha ⁻¹	100 to 350 kg.ha ⁻¹
Range N rate used 2020-2004	115 to 193 kg.ha ⁻¹	20 to 400 kg.ha ⁻¹	330 kg.ha ⁻¹	40 to 180 kg.ha ⁻¹	0 to 90 kg.ha ⁻¹	110 to 352 kg.ha ⁻¹	100 to 350 kg.ha ⁻¹
Data N rate	Incitec Pivot (2018) district rates from 1996 to 2016; Thorburn and Wilkinson (2013) district rates 2004-2008; P2R survey data basin rates from 2018 to 2024	Tree crops 150 kg.ha ⁻¹ (Thorburn and Wilkinson, 2013); Macadamias 62 to 200 kg.ha ⁻¹ (O'Hare et al. 2004; Stork et al. 2007, 2009; Irvine-Brown et al. 2024a); Avocados 69 to 528 kg.ha ⁻¹ average: 212 kg.ha ⁻¹ (Newett et al. 2018; Irvine-Brown et al. 2024b); Pawpaw 220 to 440 kg.ha ⁻¹ (Ross et al. 2000); Mangoes 14 to 27 kg.ha ⁻¹ (Meurant et al. 1999); Citrus 60 to 190 kg.ha ⁻¹ (Leeks, 2019; Owen-Turner et al. 1997); Pineapples 78 to 560 kg.ha ⁻¹ average 450 kg.ha ⁻¹ (Newett, 2017)	520 kg.ha ⁻¹ (Daniells 1995) 1994 survey; Armour et al. (2013) early 2010 rates; Thorburn and Wilkinson (2013) early 2010 rates; King (2021); P2R rates 2018-2023. Australian Banana Growers' Council survey data (2023-2024) rates highly variable between 120 up to 500 kg.ha ⁻¹ (industry district average rate 330 kg.ha ⁻¹)	Capsicum and tomatoes 216 kg.ha ⁻¹ (Thorburn and Wilkinson (2013); Sweet corn 160 to 250 kg.ha ⁻¹ (Wright et al., 2005; Stork et al. 2007; Harper 2014); Capsicums 60 to 220 kg.ha ⁻¹ (Olsen 1992; Meurant et al. 1999; Stork et al. 2007); Tomatoes 50 to 160 kg.ha ⁻¹ (Fullelove et al. 1998); Potatoes 180 kg.ha ⁻¹ Lockyer Valley example (Jackson et al. 1997); Melons 60 to 120 kg.ha ⁻¹ (Wright et al. 1997); Pumpkins 80 kg.ha ⁻¹ in Mareeba and 150 kg.ha ⁻¹ in the Burdekin (Armour and Ford, 1996)	Grains (100 kg.ha ⁻¹) (Thorburn and Wilkinson, 2013)	Irrigated and rainfed (265 and 110 kg.ha ⁻¹ , respectively) (Thorburn and Wilkinson, 2013); Annual Cotton Research and Development Corporation surveys (2016-2024). Roth (2009); Roth Rural (2017)	200 to 500 kg.ha ⁻¹ Koci and Nelson (2016)
Range P rate used 1990-1995	15 to 40 kg.ha ⁻¹	10 to 50 kg.ha ⁻¹	68 kg.ha ⁻¹	20 to 60 kg.ha ⁻¹	0 to 30 kg.ha ⁻¹	23 kg.ha ⁻¹	45 to 80 kg.ha ⁻¹

Metric	Sugarcane	Fruit and nuts (minus bananas)	Bananas	Vegetables	Field crops (minus cotton)	Cotton	Pastures
Range P rate used 2020-2004	15 to 23 kg.ha ⁻¹	10 to 50 kg.ha ⁻¹	30 kg.ha ⁻¹	20 to 60 kg.ha ⁻¹	0 to 30 kg.ha ⁻¹	10 to 44 kg.ha ⁻¹	45 to 80 kg.ha ⁻¹
Data P rate	Incitec Pivot (2018) rates from 1996 to 2016; district rates for 2016 applied to 2024	Macadamias 15 to 20 kg.ha ⁻¹ (O'Hare et al. 2004; Stork et al. 2007); Pawpaw 80 kg.ha ⁻¹ (Ross et al. 2000); Mangoes 6 to 15 kg.ha ⁻¹ (Meurant et al. 1999); Avocados 0 to 100 kg.ha ⁻¹ average 31 kg.ha ⁻¹ (Newett et al. 2018); Citrus 14 to 35 kg.ha ⁻¹ (Leeks, 2019; Owen-Turner et al. 1997); Pineapples 0 to 77 kg.ha ⁻¹ average 20 to 40 kg.ha ⁻¹ (Newett, 2017)	68 kg.ha ⁻¹ Daniells (1995) 1994 survey; DPI&F (2007) and J. Armour (personal communication, 2013); 60 kg.ha ⁻¹ King (2021). Australian Banana Growers' Council survey data (2023-2024) rates highly variable between 0 up to 60 kg.ha ⁻¹ (average rate 30 kg.ha ⁻¹)	Sweet corn 10 to 40 kg.ha ⁻¹ (Wright et al. 2005; Stork et al. 2007; Harper 2014); Capsicums 30 to 110 kg.ha ⁻¹ (Meurant et al. 1999; Stork et al. 2007); Tomatoes 30 to 100 kg.ha ⁻¹ (Fullelove et al. 1998); Potatoes 40 kg.ha ⁻¹ Lockyer Valley example (Jackson et al. 1997); Melons 40 to 80 kg.ha ⁻¹ (Wright et al. 1997)		Nachimuthu et al. (2022); Annual Cotton Research and Development Corporation surveys (2016-2024)	0 to 80 kg.ha ⁻¹ Gourley et al. (2012)
Comparison to 1990 crops in key basins		<i>Barron: Macadamias, avocados, mangoes, citrus; Johnstone: avocados, citrus; Tully/Murray: Lychees, citrus; Waterpark: citrus, lychees, mangoes, macadamias, pineapples (540 ha); Kolan: Mangoes; Burnett: citrus, mangoes Burrum: Mangoes, citrus, pineapple, lychees; Mary: Macadamias, avocados, mangoes, stone fruit, citrus</i>		<i>Barron: peanuts, potatoes; Haughton/Burdekin: Beans, melons; Don: Tomatoes, beans, capsicum; Kolan/Burnett/Burrum: Tomatoes, melons, mixed; Mary: Beans</i>	<i>Barron: tobacco</i>		
Notes and confidence (2021 crops in key basins)	<i>Highly confident in rate data and fertilised area of sugar</i>	<i>Barron: Avocados, mangoes; Johnstone: Citrus, avocados; Tully/Murray: Avocados, macadamias; Waterpark: Mangoes, pineapples, avocados, mandarins/oranges; Kolan/Burnett/Burrum/Mary: Macadamias (some pineapples, avocados, mangoes)</i>	<i>Highly confident in rate data and fertilised area of bananas</i>	<i>Barron: Potatoes, sweet corn; Burdekin/Haughton: Melons, sweet corn; Don: Sweet corn (dominant), Capsicums, tomatoes; Kolan/Burnett/Burrum: Tomatoes, potatoes, capsicums, melons, sweet corn, mixed other vegs</i>	<i>Not all N rate applied as fertiliser</i>	<i>Highly confident in rate data and fertilised area of cotton</i>	<i>Proserpine, O'Connell, Pioneer, Plane</i>

Table 2

Contributions of synthetic N and P fertiliser for each crop grouping. Uncertainties used for the areas and fertiliser rates for the seven crop groupings to calculate the N and P application for each basin and NRM region.

Crop grouping	Sugarcane	Fruit and nuts	Bananas	Vegetables	Cotton	Field crops	Dairy pastures	Source of data or approach
2024 Area represented (ha)	280,000	37,000	10,000	20,000	49,000	750,000	12,000	ABS
2024 Area represented (%)	24%	3%	1%	2%	4%	65%	1%	ABS
2024 synthetic N applied (t)	41,000	6,600	3,500	2,900	13,000	5,200	2,600	This study
2024 synthetic N applied (%)	55%	9%	5%	4%	18%	7%	3%	This study
2024 synthetic P applied (t)	4,500	920	310	930	2,100	840	900	This study
2024 synthetic P applied (%)	43%	9%	3%	9%	20%	8%	9%	This study
Uncertainty in area (%)	± 10%	± 10%	± 10%	± 10%	± 15%	± 15%	± 20%	ABS data; higher uncertainties relate to derived from difference between total crop area and other crops and from number of dairy cows per hectare
Uncertainty in N and P fertiliser rate (%)	± 5% (±10% 2017-2024)	± 20% to ± 80%	± 10%	± 20% to ± 70%	± 10%	± 20%	± 20%	Various sources - industry sources from fertiliser company (high = ±5%); farmer survey data (moderate = ± 10%); recommended industry rates (high = ±20% to ±80%)

determined the proportion of each crop group in the statistical district that was held within each river basin. These proportions were then applied to allocate the ABS statistical district data to each river basin. This method differs from the original approach by [Lewis et al. \(2021\)](#) who drew on the total cropping area for each basin reported by the [ABS, 2008](#) from the 2006 census. The application of the QLUMP data provide a more robust methodology to inform the allocations of the statistical district data of the specific crop groupings to the river basin. However, there can be differences in the absolute cropping areas between the ABS statistics and the corresponding QLUMP mapping outputs which have been discussed in [Lewis et al. \(2021\)](#). Specifically, the QLUMP outputs provide the broad area of cropping and do not necessarily capture the area that was fertilised in an individual year (i.e. for sugarcane it will produce the total sugarcane area which includes paddocks under fallow as well as standover). Hence, QLUMP will often overestimate the area of cropping that was fertilised each year. In essence, the combination of QLUMP spatial outputs to inform the proportional allocations of the ABS statistical district data for individual crops draws on the strengths of

both methodologies and provides a robust approach to inform the basin crop area time series. Additionally, the data-scaled up to represent the NRM region have much higher confidence. For example, our allocations of the district data to basins and then summed to represent NRM region closely matched (within 5%) the corresponding ABS reports at the NRM region scale and there is also agreement with the independent QLUMP outputs (see [Lewis et al., 2021](#)).

The fine spatial scale ABS statistical data relevant to GBR river basins needed to build upon [Pulsford's \(1996\)](#) time series were available from 1990 to 1997 (inclusive), 2001, 2006, 2011, 2016 and 2021 ([ABS, 2022](#)). Linear interpolation was used to infill periods of missing data between 1998 and 2000, 2002-2005 and 2007-2008. For the periods 2009-2010, 2012-2015 and 2017-2020, NRM-scale data were available to inform and impute the basin-level data. This was done by calculating the proportional mean of the basin's contribution to its NRM region for the two bounding years. This proportion was then multiplied by the total value reported for the NRM year to produce the basin area for that year. For example, to calculate the vegetable area for the Barron Basin for

2013 we took the mean proportional contributions to the Wet Tropics NRM region for 2011 (0.836) and 2016 (0.751) (mean = 0.794) and multiplied this by the area of vegetables in the NRM region reported for 2013 (2654 ha $\times$ 0.794 = 2107 ha). The areas of vegetables were not reported at the NRM region in 2017 for the Fitzroy, 2018 for the Wet Tropics and Mackay Whitsunday and 2019 for the Burdekin and Fitzroy NRM regions. Linear interpolation was used to infill those years. Specifically, we note that sugarcane grown in the GBR catchment area has a ~ 5-year crop cycle and banana and fruit and nut crops are perennial and cycle over much longer timeframes. While vegetable crops are annual and can change on individual paddocks from year to year, the total vegetable cropping area within a basin often remains highly stable over time as evident in our data time series (Supp. Figs. 1–29). Cotton is another annual crop largely grown when there is an adequate and relatively cheap water supply, but it is grown entirely in the larger basins (predominately the Fitzroy Basin) which can be allocated directly from the NRM-scale reporting. Field crops are the exception where areas can vary greatly over successive years across the basins. However, these are low value crops, often unfertilised and hence contribute comparatively little to the total N and P applied in the basins (Table 2). We present the 1990–2024 time series for each crop group's area, as well as the N and P applied, for each basin in the supplementary material (Supp. Figs. 1–29) as well as the difference in intensive cropping land use areas between the QLUMP land use mapping outputs from 1999 to 2021 (Supp. Fig. 30). Collectively these analyses demonstrate the stability of most of the crop groupings over this period.

2.6. Fertiliser rate application data

We applied Pulsford's (1996) N and P fertiliser application amounts (kg) in 1990 for the five crop groupings coupled with the corresponding fertilised land use area (ha) to calculate N and P application rates (kg ha⁻¹) for each of these crop groupings within each basin. This provided a 'benchmark fertiliser application rate' for 1990. We note that some of the fertiliser application rates were unrealistically high or low in certain basins reflecting the difficulty Pulsford had in allocating cropping land use areas to an individual basin where statistical districts overlapped multiple basins. The basins most influenced by this issue were the Daintree, Mossman, Barron, Russell Mulgrave, Tully, Murray, Black, Ross, Haughton, Burdekin, O'Connell, Pioneer, Styx, Shoalwater, Waterpark, Kolan, Burnett and Burrum. However, when an average of these rates was applied for basins where the districts overlapped (or when upscaled to NRM region), the N and P application rates agreed with known application rates for this time (e.g. Table 1).

Incitec Pivot Fertilisers provided N and P fertiliser application rates in the sugarcane industry from 1996 to 2016 for the Wet Tropics (Tully to Mossman including Atherton Tablelands), Herbert, Burdekin, Central (Proserpine, Mackay and Sarina) and South Queensland (Bundaberg, Maryborough, Isis & Rocky Point) districts (Incitec Pivot, 2018). Survey data conducted for the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program provided basin-specific sugarcane N fertiliser rates from 2018 to 2024 (A. Northey, pers comm. 2025). We note that the dominant type of synthetic N fertiliser used in the sugarcane industry has changed over time from ammonium sulphate until the 1970s, Aqua Ammonia from the 1970s to early 1980s and urea from the 1980s to present (Kuhn, 2026). Banana rates were obtained from published literature (Armour et al., 2013), the Australian Bananas Growers' Council survey data (ABGC, unpublished data) and from Paddock to Reef Program records (A. Northey, pers comm. 2025). Thorburn and Wilkinson (2013) also provide N rates for sugarcane, bananas, tree crops, vegetables (capsicum and tomatoes), cotton and grains. Annual cotton N and P application rates from 2016 to 2024 were compiled from the Cotton Research and Development Corporation annual grower surveys (e.g. CRDC, 2024) and P rates were obtained from Nachimuthu et al. (2022). N and P fertiliser application rates for the other crops of the GBR have been compiled from various sources including industry

recommended practices/guides, field trials and the Paddock to Reef Program records and are summarised in Table 1. We note that N and P recommended rates do not always reflect current industry practice (e.g. Stork et al., 2007) and that rates will vary depending on the crop type, stage and production, growing season, soil types and nutrient contents as well as other factors. In particular, the fertiliser requirements for tree crops are based on a rate per tree which is largely informed by crop type, soil type and tree age. For fruit and nuts (minus bananas) and vegetables, our N and P rates were informed by averages reported from survey data or recommended rates for the dominant crop in the basin (Table 1). For field crops and dairy pastures, we largely drew on the rate calculated for 1990 using (Pulsford, 1996) data and the corresponding fertilised area with a particular focus on the basins with larger tonnages (>100 t) of N and P applied. We note that outside of dairy pastures there is negligible N and P applied to other pasture lands (Kuhn, 2026). Given the varying quality of the N and P fertiliser rate data across both crop type and over time, we ascribed uncertainties to the rate data (noting that these are different to the uncertainties applied to the areas of the crop groupings above) (Table 2). For fruit and nuts, and vegetables, the uncertainties were determined to capture the surveyed or recommended rate range for the dominant crops within the basin (Supp. Tables C-F).

2.7. Confidence of N and P fertiliser application for the crop groupings

Average annual district-scale N and P fertiliser rates for sugarcane coupled with documented changes in rates over time for bananas and cotton are available. Combined with reliable land use area data, this provides high confidence in the fertiliser application estimates for basins dominated by these crops. Indeed, this captures the majority of basins within the GBRCA, with the largest amounts of N and P applied. Across the entire GBRCA, these crops represent 78% of the total N fertiliser and 66% of the total P fertiliser applied (Table 2). We have more limited N and P application rates for the other crop groupings including fruit and nuts, vegetables, field crops and dairy pastures, where there are estimated rates available for points in time (Table 1) and a 1990 'benchmark' from Pulsford (1996). This provides a reasonable estimate of the N and P amounts applied in these crops, although the method will not be able to document the potential changes in rates over the whole period of this study.

2.8. Estimation of total applied N and P with uncertainty

Total fertiliser (N or P) applied is calculated as the product of crop area (A, ha) and fertiliser application rate (R, kg.ha⁻¹). Both quantities are subject to uncertainty, with the magnitude of uncertainty varying by crop type and fertiliser application rate (Table 2; Supp. Tables C-F). A Monte Carlo simulation framework was used to derive both central estimates and associated uncertainty.

Uncertainty in total applied fertiliser (N or P) was propagated from two input parameters: land use area and fertiliser application rate for key crop groupings. Each parameter was assumed to follow a lognormal distribution, because they are both positive and often have right-skewed empirical distributions consistent with standard statistical practice for such data (Limpert et al., 2001) and with the convention adopted elsewhere in GBR catchment load and concentration modelling (e.g. Kuhnert et al., 2012). We note that for many crop groupings and basins, input distributions are derived from a limited number of reported values rather than large empirical samples, preventing formal goodness-of-fit testing or non-parametric bootstrapping across the full set of distributions. We acknowledge this as a limitation of the uncertainty framework, particularly for crops subject to rapid land-use transition where a heavy-tailed or bimodal distribution may not be fully captured by the lognormal parameterisation. However, as total fertiliser applied at the basin and regional scale is derived by summing contributions across crop groupings and basins at each simulation iteration, and as the crops most exposed to rapid land-use transition (fruit and nuts, vegetables) together

represent a comparatively minor share of the overall N and P budget relative to sugarcane, bananas and cotton (78% and 66% of total N and P respectively; Table 2), the influence of any bimodality in these inputs on reported basin and region-scale uncertainty bounds is expected to be limited.

Distribution parameters were derived from reported point estimates of crop area and fertiliser application rates specific to each crop within each basin and year (1991–2024). Uncertainty for each parameter was expressed as a coefficient of variation (CV), calculated from the reported uncertainty estimates across land use categories (Table 2).

The corresponding log-scale standard deviation was computed as:

$$\sigma = \sqrt{\ln(1 + CV^2)}$$

The log-scale mean was defined such that the reported point estimate corresponded to the median of the lognormal distribution.

For each Monte Carlo iteration (i), independent random samples of land use area and fertiliser application rate were drawn and combined multiplicatively to estimate total N and P fertiliser applied:

$$F^{(i)} = A^{(i)} \times R^{(i)}$$

where $A^{(i)}$ denotes land use area and $R^{(i)}$ denotes fertiliser application rate. A total of 10,000 simulations were performed for each river basin and year.

The resulting output distributions were summarised using the median as the central estimate, with uncertainty characterised by the 2.5th and 97.5th percentiles. The median was selected as the primary estimate

because the simulated outputs were lognormally distributed and right-skewed.

To estimate uncertainty at the NRM region scale, total fertiliser applied was summed across all river basins within each NRM region for each Monte Carlo iteration and year. The resulting regional-scale distributions were then summarised using the same median and percentile-based uncertainty metrics as for the basins.

2.9. ABS fertiliser application data

The ABS provides basin-level fertiliser data for 2008/09 which included the amounts of chemical fertiliser, dunder, mill mud/ash, animal manure and other fertilisers applied to each GBR basin (ABS, 2010). We note this is the only year when such data have been made available and so it provides a case study of N and P that are applied at the river basin scale. Mill mud/ash is produced as a mill by-product during the production of sugar and is redistributed to sugarcane paddocks in the surrounding districts. Animal manure is typically applied to paddocks where there is an abundant supply; in most cases these are probably grain crops (i.e. field crops) and grazing pastures. The amounts of N and P from the chemical (or synthetic) fertilisers could not be calculated, as the specific fertiliser products were not provided and these vary in their N and P contents. However, data were provided on mill mud/ash and animal manure, which are of particular interest as they represent reutilised inputs of N and P within basins that should be considered in paddock-scale nutrient budgets.

We calculated the N and P proportions in these additives to provide a

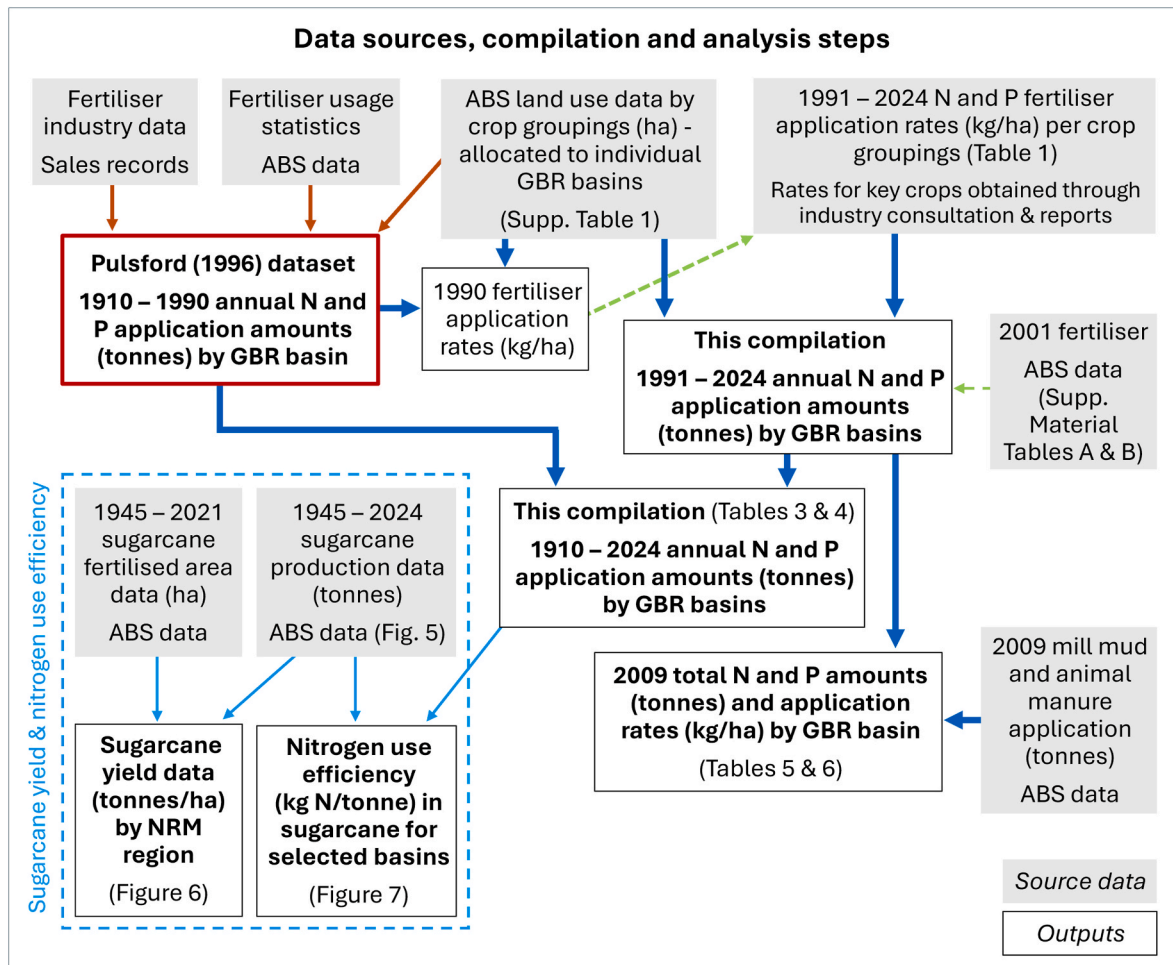


Fig. 2. Summary of method steps to compile N and P application amounts for the GBR river basins and NRM regions along with the additional analyses that have been performed on the data.

Table 3Annual synthetic N fertiliser applied (t) for the GBR basins. Interpolated values are in *italics*.

Year	Cape York	Daintree	Mossman	Barron	Russell Mulgrave	Johnstone	Tully	Murray	Herbert	Black	Ross	Haughton	Burdekin	Don	Proserpine	O'Connell	Pioneer	Plaine	Styx	Shoalwater	Waterpark	Fitzroy	Calloope	Boyne	Baffle	Kolan	Burnett	Burrum	Mary
1910									10									10											
1911									18									26											
1912									26									42											
1913									34									58											
1914									42									74											
1915					50				50			10				50	60	90											
1916					60				60			18				64	84	111											
1917					70				70			26				78	108	132											
1918					80				80			34				92	132	153											
1919					90				90			42				106	156	174											
1920			10		100	10			100			50				120	180	195									10		
1921			12		130	18			120			55				130	192	206									16		
1922			14		160	26			140			60				140	204	217									22		
1923			16		190	34			160			65				150	216	228									28		
1924			18		220	42			180			70				160	228	239									34		
1925			20		250	50			200			75		5	50	170	240	250									40		
1926			22		286	80			230			90		6	60	184	265	278									44		
1927			24		322	110			260			105		7	70	198	290	306									48		
1928			26		358	140			290			120		8	80	212	315	334									52		
1929			28		394	170			320			135		9	90	226	340	362									56		
1930		10	30	10	430	200	50		350			150	5	10	100	240	365	390			5						60		
1931		12	36	12	434	280	60		360			152	8	12	110	262	382	392			6						68		
1932		14	42	14	438	360	70		370			154	11	14	120	284	399	394			7						76		
1933		16	48	16	442	440	80		380			156	14	16	130	306	416	396			8						84		
1934		18	54	18	446	520	90		390			158	17	18	140	328	433	398			9						92		
1935		20	60	20	450	600	100		400			160	20	20	150	350	450	400			10						100	5	10
1936		22	66	36	495	700	120		418			168	26	22	160	360	483	455			12						104	8	13
1937		24	72	52	540	800	140		436			176	32	24	170	370	516	510			14						108	11	16
1938		26	78	68	585	900	160		454			184	38	26	180	380	549	565			16						112	14	19
1939		28	84	84	630	1,000	180		472			192	44	28	190	390	582	620			18						116	17	22
1940		30	90	100	675	1,100	200		490		1	200	50	30	200	400	615	675			20	5					120	20	25
1941		32	96	96	740	1,060	200		492	1	204	48	32	212	400	612	670			21	5						128	28	24
1942		34	102	92	805	1,020	200		494	1	208	46	34	224	400	609	665			22	5						136	36	23
1943		36	108	88	870	980	200		496	2	212	44	36	236	400	606	660			23	5						144	44	22
1944		38	114	84	935	940	200		498	2	216	42	38	248	400	603	655			24	5						152	52	21
1945		40	120	80	1000	900	200	30	500	2	220	40	40	260	400	600	650			25	5					10	160	60	20
1946		43	148	84	1031	946	229	35	620	2	296	74	48	270	404	611	664			26	6					15	200	71	38
1947		46	176	88	1062	992	258	40	740	2	372	108	56	280	408	622	678			27	7					20	240	82	56
1948		49	204	92	1093	1038	287	45	860	3	448	142	64	290	412	633	692			28	8					25	280	93	74
1949		52	232	96	1124	1084	316	50	980	3	524	176	72	300	416	644	706			29	9					30	320	104	92
1950		55	260	100	1155	1130	345	55	1100	3	600	210	80	310	420	655	720			30	10			5	35	360	115	110	
1951		59	278	108	1242	1214	370	59	1180	3	610	212	82	320	438	683	762			34	11			7	45	401	135	129	
1952		63	296	116	1329	1298	395	63	1260	3	620	214	84	330	456	711	804			38	12			8	56	443	156	148	
1953		67	314	124	1,416	1382	420	67	1340	4	630	216	86	340	474	739	846			42	13			10	66	484	176	168	
1954		71	332	132	1503	1466	445	71	1420	4	640	218	88	350	492	767	888			46	14			11	77	526	197	187	
1955		75	350	140	1590	1550	470	75	1500	4	650	220	90	360	510	795	930			50	15			13	87	567	217	206	
1956		79	370	148	1680	1638	496	79	1586	4	677	230	93	424	552	851	1005			52	16			15	100	597	240	220	
1957		83	390	156	1770	1726	522	83	1672	4	704	240	97	488	594	907	1080			54	16			17	112	626	262	234	
1958		87	410	164	1860	1814	548	87	1758	5	731	250	100	552	636	963	1155			56	17			18	125	656	285	247	
1959		91	430	172	1950	1902	574	91	1844	5	758	260	104	616	678	1019	1230			58	17			20	137	685	307	261	
1960		95	450	180	2040	1990	600	95	1930	5	785	270	107	680	720	1075	1305			60	18	1		22	150	715	330	275	
1961		110	525	210	2380	2325	700	110	2255	5	1020	350	140	760	930	1390	1685			70	23	3		35	220	1000	600	425	
1962		115	550	222	2480	2430	730	115	2355	5	1105	380	140	820	1045	1560	1890			80	26	6		50	300	1250	750	550	

Year	Cape York	Daintree	Mossman	Barron	Russell Mulgrave	Johnstone	Tully	Murray	Herbert	Black	Ross	Houghton	Burdekin	Don	Proserpine	O'Connell	Pioneer	Plaine	Styx	Shoalwater	Waterpark	Fitzroy	Calloope	Boyne	Baifle	Kolan	Burnett	Burrum	Mary
1963		155	740	260	3010	3230	950	135	2950		6	1715	590	220	1045	1415	2015	2495		90	52	8		80	450	1600	890	730	
1964		155	775	490	3150	3370	1010	160	3270		7	1940	665	250	1205	1330	2120	2490		100	87	10	1	82	450	1590	900	732	
1965		180	860	605	3525	3790	1140	18	3580		8	2045	705	265	1245	1535	2260	2785		110	130	17		80	455	1590	912	760	
1966		200	870	620	3550	3830	1150	19	3590		9	2360	810	305	1005	1595	2380	2985		120	140	18	2	110	680	1970	1180	820	
1967		210	875	645	3680	3640	1150	200	3600		10	2575	885	335	920	1665	2450	3015		125	200	20	2	170	860	2163	1250	950	
1968		200	820	650	3600	3760	1140	200	3630		10	2725	940	355	1170	1785	2475	3070		130	250	24	3	160	850	2155	1240	950	
1969		205	825	650	3600	3720	1130	200	3670		12	3240	1115	420	1170	2085	2990	3735		145	320	30	4	160	780	2020	1300	870	
1970		210	840	700	3910	4020	900	200	4200		10	2890	1000	380	1100	1990	2805	3555		160	235	35	4	170	800	1880	1425	1000	
1971		225	860	750	4120	4600	1000	220	4225		15	4150	1425	540	1200	2290	3235	4100		170	340	33	4	215	1040	2390	1800	1430	
1972		240	885	800	3860	4980	1200	240	4905		16	4535	1560	595	1400	2325	3290	4180		185	340	28	4	230	1110	2630	1980	1630	
1973		220	810	760	3850	4840	1140	250	4870		15	4865	1670	670	1550	2535	3580	4545		200	350	26	3	250	1190	2800	2210	1770	
1974		230	840	800	3965	5225	1300	230	5090		18	5260	1815	736	1575	2575	3640	4615		211	325	25	4	280	1350	3200	2400	1960	
1975		240	850	900	4020	5250	1260	240	5240		21	5980	2075	835	1640	2680	3790	4805		260	425	26	4	315	1570	3660	2720	2225	
1976		255	900	1050	4375	5800	1400	260	5800		23	6815	2365	995	1810	3405	4435	6160		306	790	27	4	330	1650	4000	3150	2660	
1977		305	1015	1200	4940	6540	1580	290	6555		24	7115	2475	1135	1850	3670	4780	6835		350	1385	27	5	320	1620	3970	2920	2600	
1978		245	850	1160	4020	5220	1260	260	5085		18	5450	1905	1030	1750	3085	3925	6210		352	1380	28	5	300	1350	3800	2800	2500	
1979		300	980	1390	4810	6230	1505	315	6100		18	5870	2060	1080	1770	3115	4025	5625		340	1375	28	5	300	1370	3800	2640	2600	
1980		365	1195	1690	5850	7580	1830	380	7370		25	8860	3115	1375	2650	4545	5860	8190		330	1475	28	5	420	1785	4720	3190	2705	
1981		365	1160	1540	5700	7230	1760	370	7120		22	8015	2840	1280	2390	4245	5480	7665		315	1640	35	4	400	1800	4990	3250	3105	
1982		335	1130	1485	5550	7050	1700	340	6745		23	8215	2915	1330	2500	4190	5360	7565		330	1800	40	5	380	1750	4800	3100	3050	
1983		337	1140	1480	5665	7000	1710	330	6800		24	8940	3180	1525	2640	4285	5325	7510		350	2200	45	5	385	1760	4810	3100	3045	
1984		338	1140	1450	5665	7015	1720	340	6762		19	7400	2640	1390	2120	4015	4985	6930		370	2635	53	6	400	1780	5000	3200	3060	
1985		400	1050	1445	5660	7005	1705	350	6800		20	7050	2520	1365	1780	4010	4985	6905		420	2845	62	6	410	1980	5210	3380	3095	
1986		400	1050	1440	5050	7000	1860	560	7125		16	6760	2425	1235	2020	3670	4555	6315		385	2620	70	6	400	1965	5180	3345	3100	
1987		420	1055	1610	4695	7260	2090	700	7570		16	6875	2475	1285	2015	3475	4670	6570		410	3115	72	6	415	1950	5250	3390	3150	
1988		450	1130	1650	4660	6970	2490	160	9190		17	7115	2565	1250	2060	3750	4695	6555		440	3595	70	7	430	1920	5440	3430	3140	
1989		440	945	1640	4660	6950	2480	1200	9685		18	7880	2840	1340	2500	4125	5160	7215		450	5380	63	7	400	1790	5000	3000	2980	
1990		340	820	1680	4720	7300	2660	1290	9800	5	21	8805	3180	1445	3040	4390	5490	7685		475	7290	62	7	405	1690	4545	2970	2800	
1991	8	650	730	1800	4900	8300	2500	1400	9200	820	8	7600	2600	1000	2700	3500	6000	8600	1	14	220	7300	16	97	340	1800	6900	4200	3400
1992	11	690	770	1800	4700	8500	2700	1500	9400	820	12	8200	2700	1200	2900	4800	4600	8700	1	15	220	6100	17	99	320	1700	6400	4000	3200
1993	22	670	750	1800	4500	8500	2600	1400	9700	920	12	8700	3000	1300	2800	4700	4500	8600	1	12	240	6300	25	95	330	1600	6100	3800	3300
1994	20	710	790	2000	4500	8500	2700	1500	10000	870	67	9600	3200	1400	3000	5000	4800	9000	1	14	290	5900	21	110	330	1500	6100	3600	3300
1995	35	600	670	2000	3600	7900	2300	1200	8600	640	67	7800	2700	1300	2600	4300	4100	7800	2	16	240	6600	16	86	350	950	4600	3400	2800
1996	35	610	680	2000	3400	7800	2500	1300	9300	800	46	8800	3000	1400	2900	4700	4500	8300	2	16	220	6700	43	67	390	910	4500	2900	2800
1997	26	540	590	2100	3200	7500	2600	1300	9400	930	54	9200	3100	1600	3300	5100	4900	9000	1	15	320	6600	38	65	400	950	4800	3100	3200
1998	30	490	540	2100	3100	7500	2600	1400	10000	850	47	10000	3400	1600	3300	4800	4900	8900	2	14	320	7600	32	66	420	980	5000	3300	3300
1999	33	520	570	2100	3300	7900	2800	1500	11000	740	38	12000	3900	1800	3700	5300	5700	10000	2	14	320	8500	27	67	440	980	5200	3500	3300
2000	40	540	590	2200	3600	8400	2900	1600	10000	610	30	11000	3700	1600	3000	4100	4600	8400	3	13	320	9500	22	69	460	990	5400	3700	3400
2001	44	540	590	2300	3700	8600	3000	1700	11000	540	23	11000	3900	1700	3100	4100	4900	8900	4	12	330	11000	17	70	480	1000	5600	3900	3500
2002	52	520	570	2200	3600	8200	3100	1800	12000	510	24	12000	4100	1700	3100	3900	4600	8400	3	11	330	9900	15	62	440	990	5000	3300	3100
2003	59	480	520	2200	3300	7600	3100	1700	11000	470	25	11000	3900	1700	3300	4100	4800	8500	3	11	330	9300	13	55	440	1100	4900	3200	3000
2004	65	490	530	2200	3500	7500	3300	1800	9000	400	27	12000	4100	1800	3400	4200	4900	8600	2	10	330	8700	11	48	450	1400	5100	3700	3000
2005	71	470	510	2200	3400	7100	3400	1900	8900	370	28	12000	3900	1800	3500	4100	4800	8400	1	10	330	8000	9	41	440	1500	4900	3500	2800
2006	79	460	500	2200	3400	6800	3500	1900	8700	340	30	12000	4100	1900	3700	4300	4900	8500	1	10	330	7300	7	33	450	1800	4900	3700	2800
2007	93	460	490	2600	3100	6000	3300	1900	8000	290	110	11000	3700	1600	3100	3500	4400	7300	18	11	320	5900	12	56	410	1600	4600	3100	2900
2008	94	380	400	2600	2600	5400	2900	1700	7000	270	99	10000	3300	1400	2600	2900	3700	6100	13	12	260	4500	14	59	390	1300	4400	2600	3100
2009	42	490	520	2700	3200	6100	3600	2000	9500	290	100	12000	3800	1400	3700	4200	5200	8700	13	4	230	6500	15	50	430	1600	4800	3000	3700
2010	42	380	410	2300	2600	4900	3100	1600	7000	240	87	9300	3400	990	2600	2800	3500	5900	28	14	250	5500	9	44	410	1600	4200	2900	2400
2011	77	370	390	2900	2300	4800	3100	1300	4900	200	200	7600	2900	1300	1700	2000	2900	4400	36	7	260	14000	22	85	400	1500	4900	2700	3000
2012	54</																												

Table 4
Annual synthetic P fertiliser applied (t) for the GBR basins. Interpolated values are in *italics*.

Year	Cape York	Daintree	Mossman	Barron	Russell Mulgrave	Johnstone	Tully	Murray	Herbert	Black	Ross	Haughton	Burdekin	Don	Proserpine	O'Connell	Pioneer	Plaine	Styx	Shoalwater	Waterpark	Fitzroy	Calliope	Boyne	Baffle	Kolan	Burnett	Burrum	Mary
1920					10	10			10								5	10									10		5
1921					14	14			12								6	12									13		6
1922					18	18			14								7	14									16		7
1923					22	22			16								8	16									19		8
1924					26	26			18								9	18									22		9
1925			10		30	30	10		20			10					10	20									25	5	10
1926			11		39	38	13		25			14					11	22									29	6	11
1927			12		48	46	16		30			18					13	24									33	7	12
1928			13		57	54	19		34			22					14	26									37	8	13
1929			14		66	62	22		39			26					16	28									41	9	14
1930			15		75	70	25		44			30	10		10	10	17	30									45	10	15
1931			18		84	78	28		51			35	10		12	12	21	36									56	12	18
1932			21		93	85	31		58			40	10		14	14	24	42									67	14	21
1933			24		102	93	34		64			45	10		16	16	28	48									78	16	24
1934			27		111	100	37		71			50	10		18	18	31	54									89	18	27
1935			30	10	120	108	40		78			55	10		20	20	35	60								5	100	20	30
1936			33	14	133	121	44		90			64	12		23	26	42	72								6	110	22	33
1937			36	18	146	135	48		101			73	14		26	32	49	84								7	120	24	36
1938			39	22	159	148	52		113			82	16		29	38	56	96								8	130	26	39
1939			42	26	172	162	56		124			91	18		32	44	63	108								9	140	28	42
1940		5	45	30	185	175	60		136			100	20	10	35	50	70	120			1					10	150	30	45
1941		6	46	30	192	185	64		139			104	23	14	38	54	76	128			2					10	150	30	44
1942		7	47	30	199	195	68		142			108	26	18	41	58	82	136			3					10	150	30	43
1943		8	48	30	206	205	72		144			112	29	22	44	62	88	144			3					10	150	30	42
1944		9	49	30	213	215	76		147			116	32	26	47	66	94	152			4					10	150	30	41
1945		10	50	30	220	225	80	5	150			120	35	30	50	70	100	160			5				5	10	150	30	40
1946		11	53	29	236	238	82	7	160			128	38	35	54	76	105	171			6				6	15	160	40	52
1947		12	56	28	252	251	84	9	170			136	41	40	58	82	110	182			7				7	20	170	50	64
1948		13	59	27	268	264	86	11	180			144	44	45	62	88	115	193			8				8	25	180	60	76
1949		14	62	26	284	277	88	13	190			152	47	50	66	94	120	204			9				9	30	190	70	88
1950		15	65	25	300	290	90	15	200			160	50	55	70	100	125	215			10	1			10	35	200	80	100
1951		15	65	25	303	294	90	15	213			163	51	56	77	110	136	235			12	2			11	41	244	92	119
1952		15	65	25	306	298	90	15	226			166	51	57	85	119	147	255			14	3			12	47	288	104	139
1953		15	65	25	309	302	90	15	239			169	52	59	92	129	158	275			15	5			12	54	332	116	158
1954		15	65	25	312	306	90	15	252			172	52	60	100	138	169	295			17	6			13	60	376	128	178
1955		15	65	25	315	310	90	15	265			175	53	61	107	148	180	315			19	7			14	66	420	140	197
1956		15	68	27	327	320	94	15	282			180	54	61	112	154	188	326			22	10			15	69	426	144	202
1957		16	72	29	339	330	98	16	299			185	54	61	116	161	196	337			25	12			16	72	431	148	206
1958		16	75	30	351	340	102	16	316			190	55	60	121	167	204	348			27	15			16	74	437	152	211
1959		17	79	32	363	350	106	17	333			195	55	60	125	174	212	359			30	17			17	77	442	156	215
1960		17	82	34	375	360	110	17	350			200	56	60	130	180	220	370			33	20	1		18	80	448	160	220
1961		22	105	40	480	470	140	35	446			245	72	79	145	208	253	426			36	9	1		21	103	640	152	240
1962		20	100	38	460	450	133	33	424			284	83	92	170	250	305	511			37	7	1	1	22	110	690	160	260

Year	Cape York	Daintree	Mossman	Barron	Russell Mulgrave	Johnstone	Tully	Murray	Herbert	Black	Ross	Haughton	Burdekin	Don	Proserpine	O'Connell	Pioneer	Plane	Styx	Shoalwater	Waterpark	Fitzroy	Calliope	Boyne	Baffle	Kolan	Burnett	Burrum	Mary
1963		30	160	60	740	735	210	55	680			307	87	113	240	366	445	749			41	14	2	2	24	140	917	200	300
1964		30	167	160	740	730	200	58	705			348	100	127	300	459	557	936		1	42	35	2	2	26	150	924	230	330
1965		35	175	180	780	800	226	60	710			387	111	155	285	435	527	888	3	5	43	69	3	3	28	169	958	294	405
1966		35	175	190	780	770	220	70	700			317	86	113	258	397	482	811	17	20	46	79	28	3	30	203	1150	321	562
1967		40	180	230	800	800	226	80	720			370	105	148	235	365	444	746	35	40	42	100	56	4	33	210	1220	400	720
1968		45	190	240	810	780	300	90	720			350	101	127	220	343	417	700	50	60	38	73	100	5	37	215	1215	410	860
1969		60	215	300	840	1048	360	100	720			304	86	108	267	410	496	837	45	50	38	98	95	5	40	220	1150	428	905
1970		70	236	330	870	1296	430	135	720			339	92	123	290	484	576	953	45	45	40	102	90	6	46	232	1250	660	1101
1971		72	240	403	880	1300	650	140	565			236	65	96	196	449	533	882	50	40	45	81	90	7	62	250	1282	690	1243
1972		80	250	436	880	1400	760	150	646			256	72	127	308	447	530	878	55	50	40	80	100	7	69	280	1410	730	1350
1973		80	245	445	880	1300	650	140	600			333	80	164	290	446	530	877	60	80	38	90	110	7	155	290	1467	740	1340
1974		85	250	490	870	1400	640	140	525			271	73	134	282	492	584	965	35	45	36	67	131	8	95	300	1512	720	1300
1975		80	260	485	865	1300	460	150	600			254	73	141	290	512	609	1007	7	8	38	73	32	3	100	366	1636	680	738
1976		85	280	460	900	1450	470	155	700			266	73	129	330	546	648	1071	8	10	40	120	40	2	41	380	1718	710	1050
1977		85	300	465	920	1400	480	160	750			303	83	166	320	524	622	1028	8	13	35	126	26	2	46	370	1500	660	950
1978		80	280	455	900	1300	470	155	700			259	76	197	229	477	566	936	15	35	37	127	30	2	99	350	1267	650	1020
1979		90	300	563	950	1650	500	150	720			341	101	212	240	500	593	982	10	38	40	163	30	2	91	360	1212	660	1100
1980		100	350	600	1220	1950	1600	180	1000			484	147	233	360	576	684	1130	8	44	44	194	28	2	62	378	1206	684	1260
1981		120	245	660	1215	1890	515	160	950			532	164	266	377	609	732	1125	5	50	40	241	17	2	55	390	1426	730	1180
1982		100	200	660	865	1700	485	150	970			679	217	271	350	578	695	1046	6	40	50	254	18	2	49	360	1255	750	1150
1983		110	225	670	865	1650	520	150	950			485	157	264	360	593	713	1094		35	60	286	17	2	50	340	1070	650	1260
1984		120	220	630	820	1600	500	160	1020			450	146	269	267	524	632	965	5	30	77	311	17	2	64	330	1100	678	1210
1985		110	220	580	770	1550	520	170	980			432	136	231	205	443	533	819	4	30	75	361	20	2	66	330	1007	610	1270
1986		100	220	540	700	1500	510	160	1000			404	136	206	270	428	518	789	3	28	70	288	15	2	66	300	980	580	1010
1987		115	220	510	625	1450	527	200	1070			342	143	246	307	433	524	798	2	25	75	388	14	2	102	350	1200	660	1100
1988		110	210	546	600	1400	520	210	1100			434	181	245	300	458	550	846	2	22	70	389	20	2	108	345	1100	582	950
1989		100	220	580	600	1600	520	215	1200			529	221	327	330	494	594	912	3	25	72	658	20	2	106	350	1160	600	1000
1990		100	240	625	605	1700	530	220	1330			613	256	380	459	539	648	995	3	27	73	786	20	2	105	360	1160	650	1050
1991	10	110	130	450	710	1500	330	200	1300	100	2	530	230	240	410	360	610	1000	1	5	18	760	8	26	78	380	1600	940	1200
1992	9	120	130	440	710	1500	360	220	1300	100	3	620	230	270	420	520	490	1100	1	6	17	720	8	26	73	330	1400	840	1100
1993	14	110	130	440	690	1500	360	220	1300	110	3	720	280	300	390	530	500	1100	1	5	19	700	12	24	73	290	1400	770	1200
1994	23	120	130	480	710	1500	380	230	1400	110	14	850	320	320	410	580	560	1100	1	6	22	710	10	27	72	260	1300	700	1200
1995	15	99	110	480	580	1400	330	200	1200	80	15	750	300	340	520	500	970	1	6	19	770	8	21	73	160	960	620	960	
1996	18	100	110	480	560	1400	370	220	1300	97	8	900	350	320	370	590	560	1100	1	6	17	750	12	18	79	150	950	510	990
1997	17	89	99	510	530	1400	390	220	1300	110	9	930	350	370	430	660	640	1200	1	6	25	730	11	18	83	170	1100	600	1200
1998	13	79	87	490	490	1300	390	220	1300	97	8	1000	380	400	490	590	600	1100	1	6	25	830	10	17	87	170	1100	620	1200
1999	13	69	75	470	450	1300	380	220	1200	77	7	1000	390	360	390	550	590	1100	1	6	25	930	9	16	87	150	1000	570	1200
2000	14	83	91	470	550	1500	440	260	1200	67	6	1100	410	340	310	420	480	880	1	5	25	1000	9	16	94	160	1100	670	1300
2001	15	86	94	470	590	1500	470	280	1800	67	5	1000	400	350	360	470	560	1000	2	5	25	1100	8	15	100	180	1200	780	1300
2002	16	71	77	460	500	1400	450	260	1500	58	5	950	370	330	260	330	400	720	1	5	25	1100	7	13	92	160	1000	600	1200
2003	18	73	79	470	520	1400	480	280	1400	53	5	1100	410	340	290	360	420	760	1	4	25	1000	6	12	91	190	1000	650	1100
2004	20	68	74	480	500	1300	490	280	990	42	5	1200	440	350	280	330	400	700	1	4	25	990	5	11	92	250	1000	730	1100
2005	21	70	76	490	510	1200	530	290	990	40	5	1300	470	350	270	310	370	640	1	4	25	930	4	9	88	250	980	690	980
2006	23	77	85	510	570	1300	590	330	1100	39	6	1100	400	390	400	460	540	920	1	4	25	870	3	8	89	300	980	760	940
2007	21	63	67	530	420	910	380	240	950	32	16	910	350	360	360	400	510	840	3	4	25	680	3	11	83	300	990	670	1000
2008	26	34	35	530	250	700	240	170	610	25	12	640	250	270	190	220	270	450	2	5	20	430	3	11	78	220	920	530	1100
2009	31	66	71	560	440	880	400	250	1500	37	15	930	350	310	500	570	710	1200	3	2	18	820	3	8	86	270	1000	610	1300
2010	11	51	54	460	340	670	330	200	1100	29	15	830	430	200	280	310	390	650	4	6	19	960	3	10	84	300	870	630	770
2011	33	47	49	600	280	700	310	160	650	22	26	620	420	310	170	210	290	440	5	3	20	2600	4	13	80	250	1000	540	970
2012	20	51	63	830	390	770	470	270	1300	26	15	1100	560	320	310	340	430	750	9	2	8	1800	2	5	79	210	940	570	900
2013	12	50	60	550	380	650	460	270	1100	24	15	910	390	260	220	240	300	540	5	7	12	1200	2	8	78	240	900	630	770
2014	20	48	58	520	380	730	420	310	920	21	20	980	510	270	260	290	360	640	8	8	15	1000	2	7	83	250	860	630	780
2015	9	40	48	490	300	700	360	220	790	22	17</																		

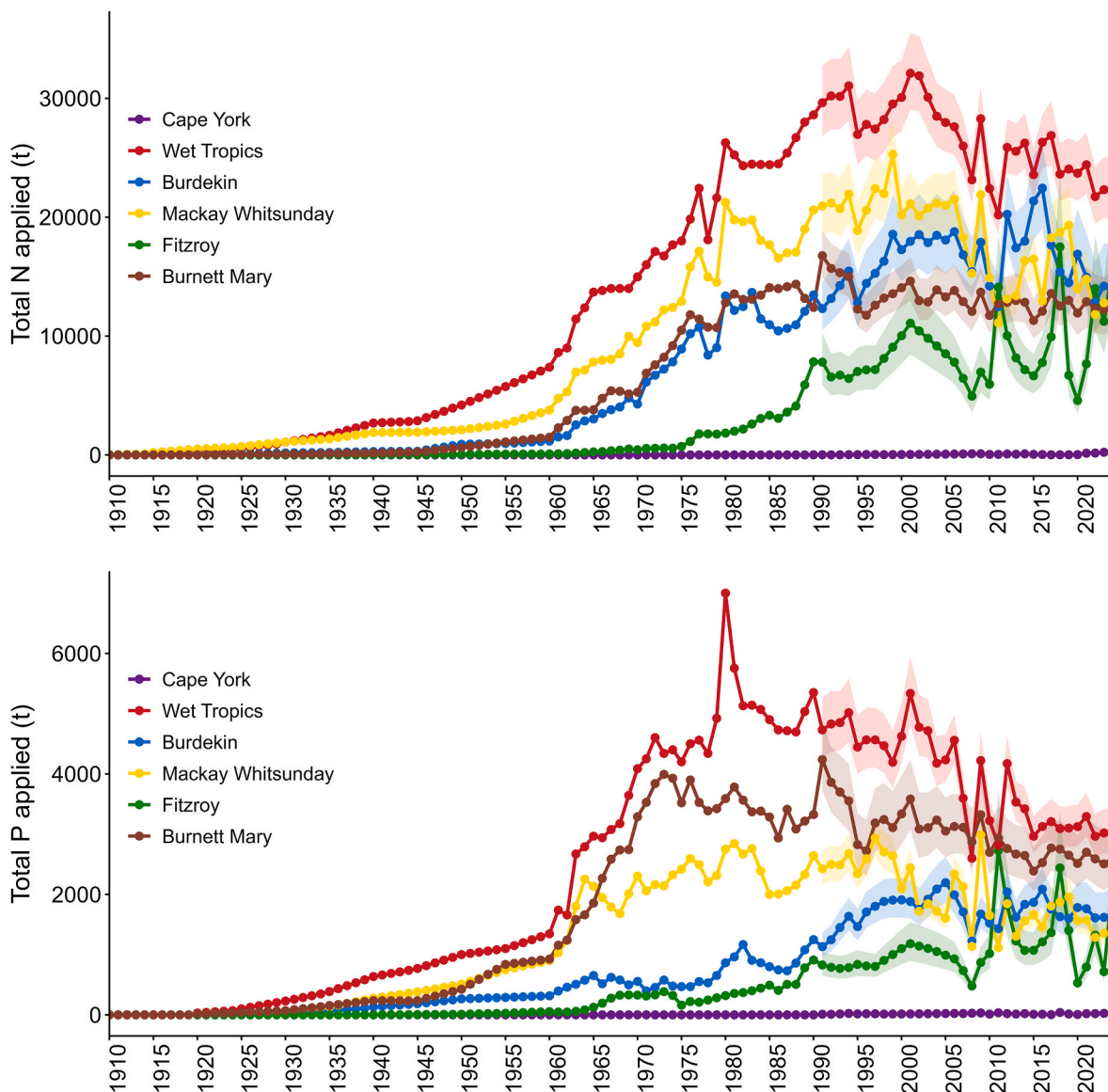


Fig. 3. Time series of synthetic N (top) and P (bottom) fertiliser applied at the NRM regions between 1910 and 2024. 1910 to 1990 data are derived from Pulsford (1996). Shaded 95% uncertainty intervals were based on Monte Carlo permutations to provide an estimate of uncertainty over our study period (1991–2024).

first order estimate of the “full N and P rate” applied to sugarcane crops in the GBR river basins for 2009. As an approximation, we have calculated the amounts of ‘plant available’ N and P in mill mud/ash and cow manure, assuming the animal manure is predominately from cattle, given the prevailing land use in the GBRCA. N and P contents in mill mud/ash vary across the different sugar mills. We have applied paddock application rates (i.e. N and P contents in an application of 100 wet tonnes of mud/ash per hectare) obtained from various mills where data were available. The data were provided in different forms whereby some sugar mills provided individual application rates for wet mill mud and wet mill ash while others provided a wet mud/ash combination. As the ABS data report dry mud/ash together, we calculated a combined mud/ash rate for the sugar mills that provided the data separately assuming a mix of 87% mud and 13% ash (based on the total mill mud and mill ash produced in Queensland: Moody and Schroeder, 2014). The moisture content of wet mill mud/ash averages 75% (Moody and Schroeder, 2014) and so the ABS dry mill mud/ash estimates were scaled up by a factor of 4 to reflect wet mud amounts in order to calculate the N and P contents. We have assumed the plant available N and P in the mill mud/ash to range between 16% and 50% and 53% and 86%,

respectively as reported in studies by Moody and Schroeder (2014) and Soil, Catchment and Riverine Processes, 2023.

The rates based on 100 wet tonnes per hectare of mill mud/ash include 241 kg ha⁻¹ N and 128 kg ha⁻¹ P for the Tully Mill in the Tully Basin (G. Shannon, pers comm, 2026) and, based on information provided by P. Larsen (pers comm, 2026): 261 kg ha⁻¹ N and 212 kg ha⁻¹ P as an average of the Victoria and Macknade Mills (Herbert Basin), 181 kg ha⁻¹ N and 271 kg ha⁻¹ P as an average of the Invicta, Pioneer, Kalamia and Inkerman Mills (Haughton and Burdekin Basins), 180 kg ha⁻¹ N and 170 kg ha⁻¹ P for the Proserpine Mill (Proserpine and O’Connell Basins) and 250 kg ha⁻¹ N and 180 kg ha⁻¹ P for the Plane Creek Mill (Plane Basin). The N and P contents (in percent) per tonne of mud/ash can be calculated by dividing these rates by 100,000. For the basins where N and P contents of mill mud were not available, we applied the contents for the Tully Mill to estimate the N and P applied for the other Wet Tropics basins (i.e. Daintree, Mossman, Russell-Mulgrave, Johnstone and Murray), an average of the Proserpine and Plane Creek Mills for the Pioneer Basin (i.e. 215 kg ha⁻¹ N and 175 kg ha⁻¹ P) and the Plane Mill to estimate the N and P contents for the Burnett Mary NRM Basins (i.e. Kolan, Burnett, Burrum and Mary).

For cow manure, we have used an average concentration of 2.0% for N and 0.5% for P of which 25% and 30%, respectively are available to plants. For a first-order approximation and to illustrate the concept of the extra N and P applied to crops, we have assumed that all the mill mud/ash and animal manure reported by the ABS was applied to the whole sugarcane cropping area in the GBR river basins. While this is not realistic (and will be discussed later), our compilation is focussed on the broader basin-scale N and P fertiliser applications and not on the finer-scale paddock/farm level.

An illustration of the method steps including the key data sources, analyses and outputs are summarised in Fig. 2.

3. Results

3.1. N and P GBR basin scale time series

The time series data indicate that, with the exception of Cape York, Styx (N only) and Fitzroy (N only), the synthetic N and P fertiliser application to GBR river basins have either declined or been relatively stable over the past one to two decades (Tables 3 and 4; Supp. Figs. 31–59). The data show that synthetic N fertiliser applied to basins

such as the Proserpine, O'Connell, Plane and Burnett (Supp. Figs. 45, 46, 48, 57) peaked in the 1990s, whereas the amount of N applied peaked for the Johnstone, Herbert and Mary Basins (Supp. Figs. 36, 39, 59) in the early 2000s. The peak for other basins such as the Barron, Tully, Haughton and Burdekin (Supp. Figs. 34, 37, 42, 43) did not occur until the mid-2010s while the Russell Mulgrave peaked as early as the 1980s (Table 3; Supp. Fig. 35). In general, the application of synthetic P fertiliser followed similar trends to N, although the peaks in application were often not as pronounced (Table 4; Supp. Figs. 31–59).

When comparing five year averages around peak fertiliser application time periods with the averages from the last 5 years, marked reductions (> 20%) were observed in nearly all basins with the exceptions of Cape York, Barron, Don, Styx, Fitzroy (N only), Kolan, Burnett (N only) and Burrum (N only). Basins with the largest reductions (>2000 t) from peak synthetic N fertiliser application include Russell Mulgrave, Johnstone, Herbert, Haughton, Pioneer, O'Connell and Plane, while the largest reductions (>400 t) from peak synthetic P fertiliser application include the Russell-Mulgrave, Johnstone, Herbert, Plane, Fitzroy, Burnett and Mary. Several basins have recorded their peak N fertiliser application over the past decade including Cape York, Daintree, Tully, Haughton, Burdekin, Styx, Shoalwater, Fitzroy and Kolan while P

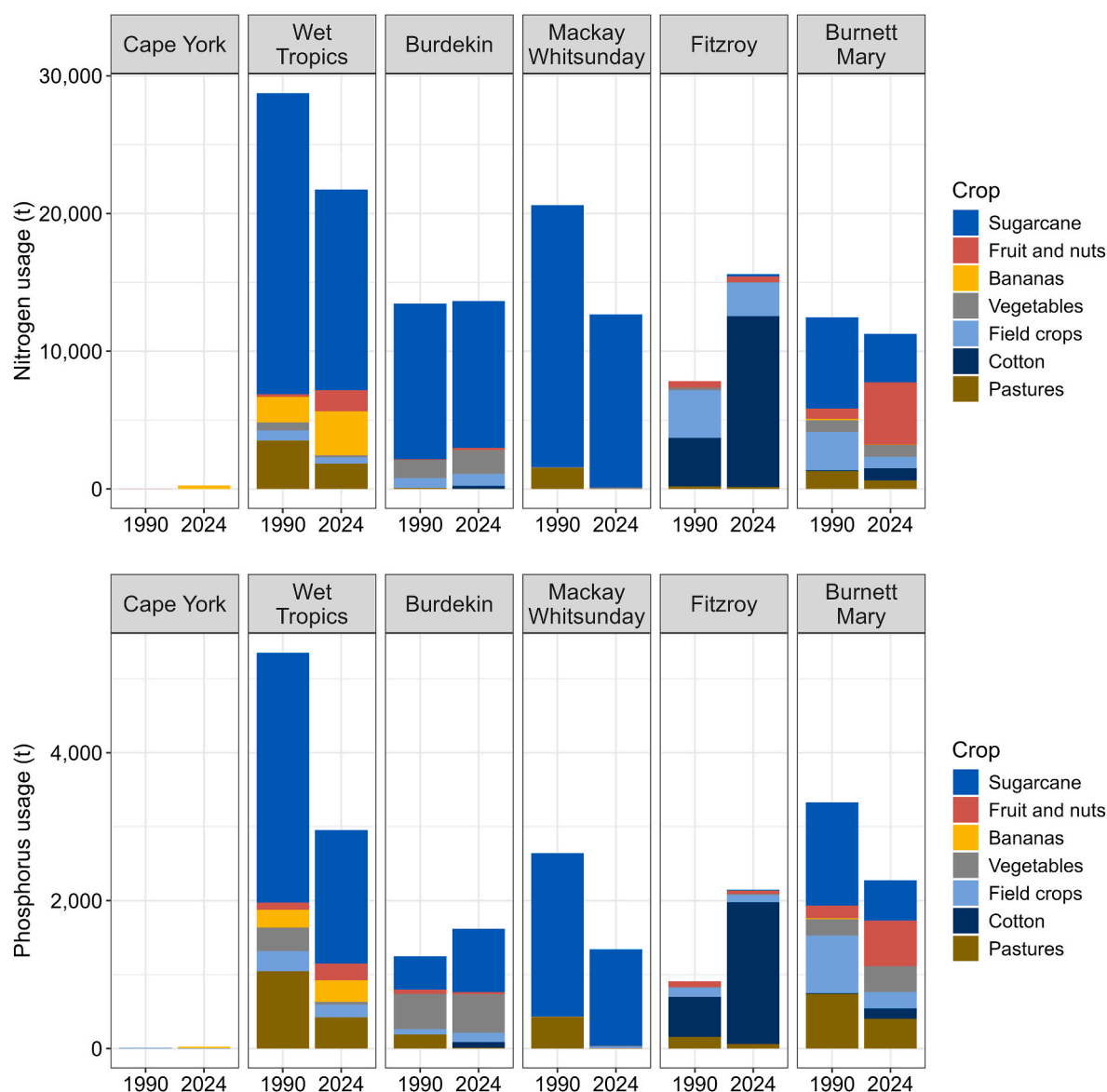


Fig. 4. Stacked bar graph of NRM region contributions from the seven different crop groupings from 1990 and 2024 for Nitrogen (top) and Phosphorus (bottom).

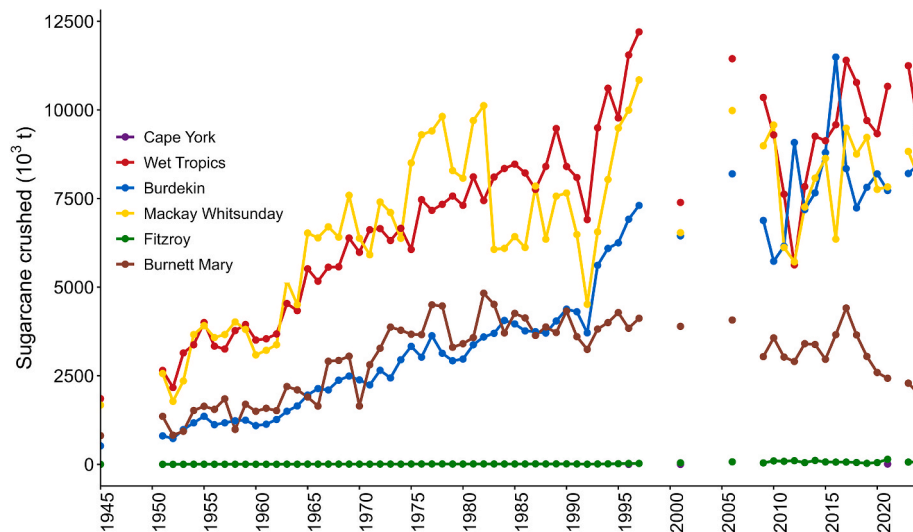


Fig. 5. Tonnes of sugarcane crushed (cut for crushing) at the NRM scale from 1945 to 2024. Based on ABS data.

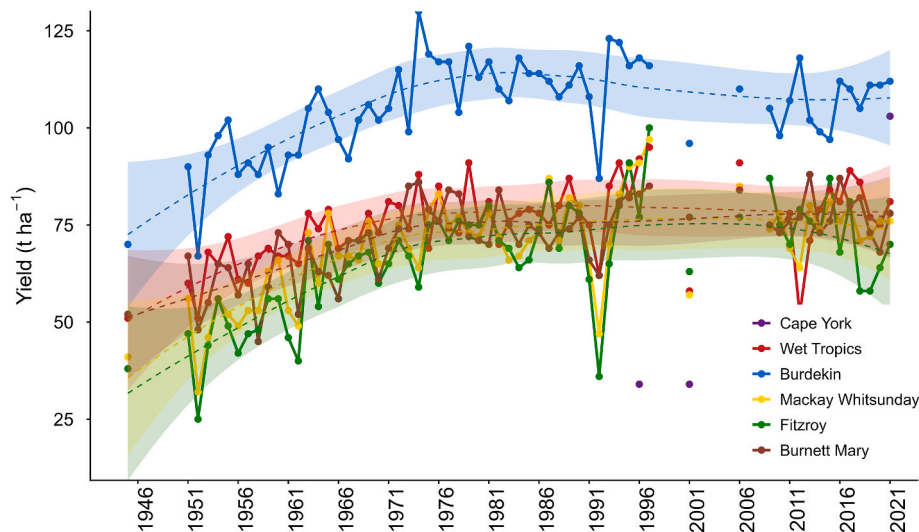


Fig. 6. Sugarcane yield (tonnes crushed per hectare of cane cut for crushing) at the NRM scale from 1945 to 2021. Temporal trends in sugarcane yield were estimated using LOESS (local polynomial regression) smoothing. Shaded ribbons indicate 99.9% uncertainty intervals around the smoothed trend for each NRM region. Based on ABS data.

fertiliser application has peaked only in the Cape York region over the past decade (Supp. Figs. 31–59).

The width of the 95% uncertainty intervals generated by the Monte Carlo simulations of basin-scale N and P application amounts (i.e. the difference between the 97.5th and the 2.5th percentiles, expressed as a percentage of the median) are in the order of ± 36 to 52% for most basins, although larger uncertainties of ± 55 to 256% are evident for some of the basins with low fertiliser application amounts (e.g. Cape York, Black, Ross, Styx, Shoalwater, Waterpark, Calliope, Boyne, Baffle), or for basins which contain more mixed land uses such as the Don, Kolan, Burnett and Burrum (Supp. Figs. 31–59).

3.2. N and P GBR NRM region scale time series

The NRM scale data show that synthetic N applied in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions rose steeply from the 1960s and 1970s (Fig. 3a). The total basin and NRM scale N and P applications were estimated using Monte Carlo simulations, which accounted for uncertainty in both crop area and fertiliser

application rates, with 10,000 simulation runs used to derive medians and 95% uncertainty intervals. In the Wet Tropics N application peaked at 32,000 (29,100 – 35,500) tonnes in 2001 and the Mackay Whitsunday NRM region peaked in 1999 at 25,300 (22,500 – 28,300) tonnes. In comparison, the synthetic N fertiliser peaked in the Burnett Mary much earlier in 1991 at 16,700 (15,000 – 18,900) tonnes while the Burdekin peak of 22,300 (19,100 – 26,300) tonnes occurred much later in 2016 (Fig. 3a). The Fitzroy NRM region increased more steadily from the 1970s to 1980s and has fluctuated over the past four decades with a peak in 2018 of 17,300 (12,700 – 23,700) tonnes. N application has been relatively negligible in the Cape York region compared to the other NRM regions, peaking in 2024 at 250 (190– 320) tonnes. The amounts of synthetic N fertiliser applied in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary NRM regions have declined considerably over the past one to two decades where the latest applications are well below the peak application periods (and associated uncertainties) (Fig. 3a). From their respective N application peaks to the latest 2024 levels, the declines in synthetic fertiliser were 31% for the Wet Tropics, 37% for the Burdekin, 49% for the Mackay Whitsunday and 25% for the

Table 5An approximation of additional inputs of N in sugarcane crops based on 2009 [ABS \(2010\)](#) data.

Basin	Sugarcane area fertilised (ha)	Synthetic N application rate (kg/ha)	Synthetic N applied (tonnes)	Dry mill mud/ash (tonnes)	Wet mill mud/ash (tonnes)*	Plant available N in mill mud/ash range** (tonnes)	Animal manure (tonnes)	Plant available N in animal manure (tonnes)	Total plant available N applied (tonnes)	Total N rate (kg/ha)
Daintree	3,496	132	461	4,319	17,276	7 – 21	48	0.2	468 – 483	134 – 138
Mossman	3,870	132	511	8,967	35,868	14 – 43	..	0	525 – 554	136 – 143
Barron	4,624	132	610	..	..	0	584	2.9	613	133
Russell Mulgrave	20,861	132	2,754	44,467	177,868	69 – 214	13	0.1	2,822 – 2,968	135 – 142
Johnstone	21,965	132	2,899	51,666	206,664	80 – 249	8	0.04	2,979 – 3,148	136 – 143
Tully	14,888	132	1,965	43,574	174,296	67 – 210	2,825	14	2,047 – 2,189	137 – 147
Murray	10,604	132	1,400	12,784	51,136	20 – 62	77	0.4	1,420 – 1,462	134 – 138
Herbert	59,216	153	9,060	67,713	270,852	113 – 353	..	0	9,173 – 9,414	155 – 159
Black	810	153	124	..	..	0	..	0	124	153
Ross	402	153	61	..	..	0	..	0	61	153
Haughton	45,581	231	10,529	98,681	394,724	114 – 357	..	0	10,644 – 10,886	234 – 239
Burdekin	14,651	231	3,384	14,700	58,800	17 – 53	12,100	61	3,462 – 3,498	236 – 239
Don	4,332	177	767	140	560	0 – 1	190	1.0	768	177
Proserpine	20,554	177	3,638	42,843	171,372	49 – 154	429	2.2	3,690 – 3,794	180 – 185
O'Connell	23,441	177	4,149	43,899	175,596	51 – 158	..	0	4,200 – 4,307	179 – 184
Pioneer	29,337	177	5,193	88,214	352,856	121 – 379	125	0.6	5,315 – 5,573	181 – 190
Plane	48,834	177	8,644	90,241	360,964	144 – 451	419	2.1	8,790 – 9,097	180 – 186
Fitzroy	403	177	71	..	..	0	17,771	89	160	397
Baffle	796	143	114	..	..	0	204	1.0	115	144
Kolan	8,213	143	1,174	3,084	12,336	5 – 15	2,791	14	1,193 – 1,204	145 – 147
Burnett	10,083	143	1,442	41,210	164,840	66 – 206	57,680	288	1,796 – 1,936	178 – 192
Burrum	13,629	143	1,949	37,555	150,220	60 – 188	670	3.4	2,012 – 2,140	148 – 157
Mary	7,832	143	1,120	15,554	62,216	25 – 78	5,764	29	1,174 – 1,227	150 – 157

*assume 75% moisture content

**assume range of 16% to 50% plant available (Moody and Schroeder, 2014; Soil, Catchment and Riverine Processes, 2023)

Burnett Mary. The time series data display some year-to-year variability with some noted lows and highs; for example, anomalously low synthetic fertiliser application was recorded across the Wet Tropics, Burdekin and Mackay Whitsunday NRM regions in 2011 (Fig. 3a).

Synthetic P fertiliser application amounts for the Wet Tropics, Mackay Whitsunday and Burnett Mary NRM regions rose steeply from the 1960s but then remained at fairly consistent levels between the 1970s/1980s and early 2000s before declining over the past one to two decades (Fig. 3b). The steep increase in synthetic P fertiliser application in the Burdekin NRM region occurred much later during the late 1980s to early 1990s and has remained fairly constant since the mid-1990s, peaking in 2005 at 2200 (1900 – 2600) tonnes. In comparison, the Fitzroy NRM region has had generally much lower quantities of synthetic P fertiliser applied and, the amounts have remained relatively stable from the 1990s to mid-2000s, although marked year-to-year fluctuations have occurred over the past two decades. Distinct peaks occurred in 2011 at 2700 (2000 – 3700) tonnes and in 2018 at 2400 (1700 – 3400) tonnes. Similar to N, synthetic P fertiliser application has been negligible in the Cape York region relative to the other NRM regions peaking in 2018 at 38 (24 – 59) tonnes (Fig. 3b). The 2024 synthetic P data show that the Wet Tropics is 57% lower than the peak of 7000 tonnes applied in 1980, the Mackay Whitsunday is 55% lower than the peak of 3000 (2700 – 3300) tonnes in 2009 and the Burnett Mary is 39% lower than the peak of 4200 (3700 – 4900) tonnes in 1991.

3.3. Changing N and P basin and NRM profiles from 1990 to 2024

Time series plots of the land use groupings for each basin over the 1990 to 2024 period highlight the key crops within each basin (Supp. Figs. 1–29). We compiled the quantities of N and P fertiliser applied for each crop group and river basin for the study time series boundary years 1990 (i.e. the end of Pulsford's time series) and 2024 (i.e. the end of this study time series). A comparison of proportional contributions of each crop group to total basin N and P in 1990 and 2024 highlights changes in synthetic N and P fertiliser application within each basin (Supp. Tables 2 and 3; Supp. Figs. 1–29). For example, the data highlight the increasing amount of N and P applied in the Barron Basin associated with the expansion of sugarcane, fruit and nuts and banana crops at the expense of vegetables, field crops and dairy pastures (Supp. Fig. 4). The data demonstrate the increasing influence of bananas in the Russell Mulgrave and Johnstone Basins with reducing contributions from sugarcane, although a decrease occurred in total fertiliser applied in both basins (Supp. Tables 2 and 3; Supp. Figs. 5–6). A decline in sugarcane N and P tonnes applied (and associated lowered contributions to total basin N and P) is also evident in the Kolan, Burnett and Burrum Basins which coincide with increased contributions from fruit and nuts (predominantly macadamias), vegetables (Kolan) and cotton (Burnett) (Supp. Figs. 25–28). The proportional contributions of sugarcane to total basin N and P fertiliser application have remained generally stable for other basins such as the Mossman, Herbert, Proserpine, O'Connell, Pioneer and Plane, although the data show considerable declines in total application amounts for these basins (Supp. Tables 2 and 3; Supp. Figs. 33, 39, 45–48). Finally, between the 1990 and 2024 periods, some basins display general increases in fertiliser N and P application amounts including the Barron (N only), Murray, Ross, Haughton, Burdekin (P only), Don, Styx, Fitzroy, Boyne, Burnett (N only), Burrum (N only) and the Cape York NRM region (Supp. Tables 2 and 3; Supp. Figs. 31, 34, 38, 41, 42, 43, 44, 49, 52, 54, 57, 58).

At the NRM scale, the comparison between the 1990 and 2024 synthetic N and P amounts applied across the crop groups show decline in application in the Wet Tropics, Mackay Whitsunday and Burnett Mary NRM regions (Fig. 4). In the Burdekin NRM region, agricultural expansion in the 1990s following the construction of the Burdekin Falls Dam (built in 1987) led to an increase in the sugarcane and vegetable growing areas while in the Fitzroy region, the area of cotton increased greatly over this period (Fig. 4). The broad-scale data also highlight the

increasing influence of bananas in the Wet Tropics NRM region and macadamias (i.e. fruit and nuts) in the Burnett-Mary NRM region (Fig. 4).

3.4. Additives of non-synthetic fertilisers

Measures of the additional N and P added to cropping through soil conditioners/additives such as mill mud/ash and animal manure were calculated using the ABS, 2010 2008/09 statistics. We note that these ABS, 2010 data have considerable uncertainty with estimates varying between “relative standard error of 10% to less than 25%” and “relative standard error between 25% and 50%”. While the ABS, 2010 recommends that the data “should be used with caution” these outputs provide the only available basin-scale approximation of application and provide an indication of the N and P reutilised within each river basin.

Tables 5 and 6 present the amount of N and P, respectively, applied to sugarcane in 2009 in each of the GBR river basins from synthetic fertilisers using the fertilised area and the reported application rate for that year (i.e. this study), together with the quantities of N and P added through application of mill mud/ash and animal manure. The data show that, in the basins hosting large areas of sugarcane (i.e. >10,000 ha), mill mud/ash applications could provide an additional 1% to 11% extra plant available N and, 18% to 150% extra plant available P on top of synthetic fertiliser inputs. On a basin-scale, application of mill mud/ash increases the average plant available N rate in sugarcane by approximately 2 to 15 kg ha⁻¹ (Table 5) and increases the available P rate by approximately 3 to 20 kg ha⁻¹ (Table 6).

The contribution of N and P in animal manure is much lower with the exception of the Burnett. The largest amounts of animal manure applied to cropping areas occur in the larger grazing catchments of the Burdekin, Fitzroy, Burnett and Mary Basins suggesting that it is likely applied to grain or pasture crops growing adjacent to grazing lands.

3.5. Sugarcane production and N use efficiency

Our assembled fertiliser application time series provides an opportunity to evaluate the long-term trends in agricultural production and nutrient use efficiency since 1945. Here, we focused on the synthetic N used in the sugarcane industry which currently (2024) contributes 55% of the total synthetic N fertiliser applied across the GBRCA (Table 2). On an NRM-scale, the total tonnes of sugarcane cut for crushing rose steeply in the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary NRM regions from 1945 to the 1990s (Fig. 5). The amount of sugarcane produced has steadied in the former three regions over the past few decades and declined in the Burnett Mary region. The Fitzroy and Cape York NRM regions contribute very low and no sugarcane, respectively and will not be considered here further. In terms of sugarcane tonnes per hectare yield, the data show general increases in yield for the main producing NRM regions from the 1940s to 1970s and a relatively consistent yield thereafter (Fig. 6). Average sugarcane crop yields from 1980 to 2021 are highest in the Burdekin (110 ± 8.0 t ha⁻¹) followed by the Wet Tropics (78 ± 9.2 t ha⁻¹), Burnett Mary (76 ± 6.1 t ha⁻¹) and Mackay Whitsunday (75 ± 9.8 t ha⁻¹) NRM regions.

The plots of basin-averaged sugarcane N fertiliser application rates (kg N.ha⁻¹) and N use efficiency (kg N applied per tonne sugarcane harvested, kg N.t⁻¹ cane) for the Daintree-Mossman, Russell Mulgrave, Herbert, Haughton-Burdekin, Proserpine, O'Connell-Pioneer, Plane and Burrum Basins show a general increasing trend in the amount of N used to produce sugarcane (i.e. decreased N use efficiency) from 1945 to the mid 1980s (Fig. 7). Basin-averaged N application rates peaked in the 1980s and 1990s before reducing over the past two decades (Fig. 7a). Sugarcane N use efficiency generally stabilises from the 1980s to early 2000s before showing a decline over the past two decades (i.e. increased N use efficiency) (Fig. 7b). When the total kilograms of N applied to sugarcane are summed for each year and divided by the corresponding sum of the tonnes of sugarcane harvested, we can estimate the decadal N

Table 6An approximation of additional inputs of P in sugarcane crops based on 2009 [ABS \(2010\)](#) data.

Basin	Sugarcane area fertilised (ha)	Synthetic P application rate (kg/ha)	Synthetic P applied (tonnes)	Dry mill mud/ash (tonnes)	Wet mill mud/ash (tonnes) *	Plant available P in mill mud/ ash range** (tonnes)	Animal manure (tonnes)	Plant available P in animal manure (tonnes)	Total P applied (tonnes)	Total P rate (kg/ha)
Daintree	3,496	18	63	4,319	17,276	12 – 19	48	0.1	75 – 82	21 – 23
Mossman	3,870	18	70	8,967	35,868	24 – 39	..	0	94 – 109	24 – 28
Barron	4,624	18	83	..		0	584	0.9	84	18
Russell Mulgrave	20,861	18	375	44,467	177,868	121 – 196	13	0.02	496 – 571	24 – 27
Johnstone	21,965	18	395	51,666	206,664	140 – 227	8	0.01	536 – 623	24 – 28
Tully	14,888	18	268	43,574	174,296	118 – 192	2,825	4.2	390 – 464	26 – 31
Murray	10,604	18	191	12,784	51,136	35 – 56	77	0.1	226 – 247	21 – 23
Herbert	59,216	24	1,421	67,713	270,852	304 – 494	..	0	1,726 – 1,915	29 – 32
Black	810	24	19	..		0	..	0	19	24
Ross	402	16	6	..		0	..	0	6	16
Haughton	45,581	16	729	98,681	394,724	567 – 920	..	0	1,296 – 1,649	28 – 36
Burdekin	14,651	16	234	14,700	58,800	84 – 137	12,100	18	337 – 390	23 – 27
Don	4,332	24	104	140	560	1	190	0.3	105	24
Proserpine	20,554	24	493	42,843	171,372	154 – 251	429	0.6	648 – 744	32 – 36
O'Connell	23,441	24	563	43,899	175,596	158 – 257	..	0	721 – 819	31 – 35
Pioneer	29,337	24	704	88,214	352,856	327 – 531	125	0.2	1,032 – 1,235	35 – 42
Plane	48,834	24	1,172	90,241	360,964	344 – 559	419	0.6	1,517 – 1,731	31 – 35
Fitzroy	403	24	10	..		0	17,771	27	36	90
Baffle	796	24	19	..		0	204	0.3	19	24
Kolan	8,213	24	197	3,084	12,336	12 – 19	2,791	4.2	213 – 220	26 – 27
Burnett	10,083	24	242	41,210	164,840	157 – 255	57,680	87	486 – 584	48 – 58
Burrum	13,629	24	327	37,555	150,220	143 – 233	670	1.0	471 – 561	35 – 41
Mary	7,832	24	188	15,554	62,216	59 – 96	5,764	8.7	256 – 293	33 – 37

*assume 75% moisture content

**assume range of 53% to 86% plant available (Moody and Schroeder, 2014)

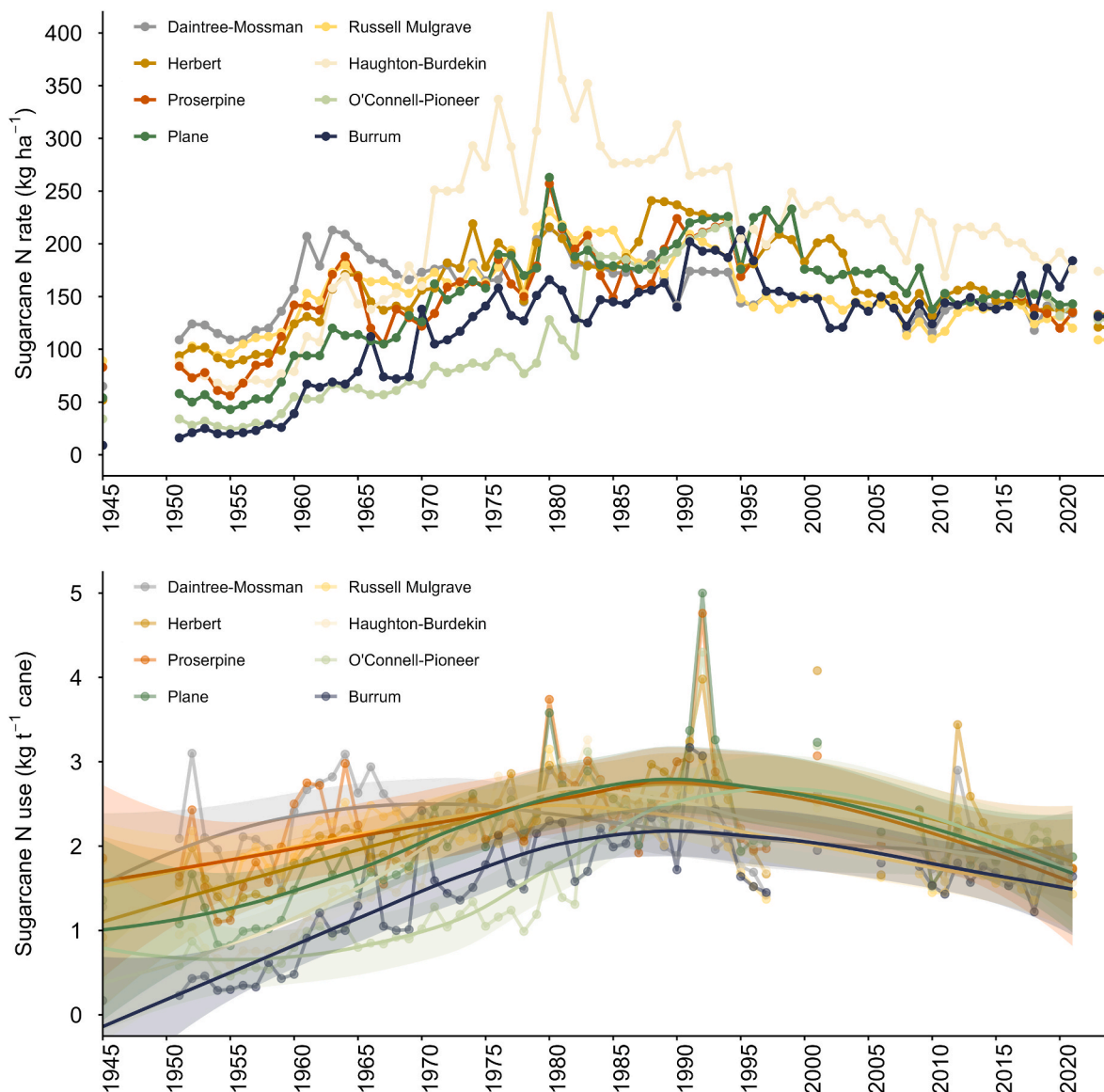


Fig. 7. Time series of synthetic N fertiliser application rates for eight sugarcane dominated basins on the GBR catchment area from 1945 to 2024 (top). The N use efficiency (kg of N per tonne of sugarcane crushed) in nine GBR river basins from 1945 to 2021 (bottom). Temporal trends in synthetic N use efficiency were estimated using LOESS smoothing. Shaded ribbons indicate 99.9% uncertainty intervals around the smoothed trend for each selected basin. Based on ABS production data.

use efficiency for these basins, which in 2024 collectively represents 77% of the sugarcane area in the GBRCA. From 1951 to 1960 the average N use efficiency across these basins, was 1.04 kgN.t⁻¹, climbing to 1.55 kgN.t⁻¹ in the 1961–1970 period, 1.99 kgN.t⁻¹ between 1971 and 1980, 2.43 kgN.t⁻¹ in the 1981–1990 period, 2.47 kgN.t⁻¹ in 1991–2000, 2.21 kgN.t⁻¹ in 2001–2010 and 1.90 kgN.t⁻¹ in 2011 to 2020. We note that the standard errors in the N fertiliser applied (in the order of ± 10 to 15%) and the sugarcane production ($\pm 10\%$) reduce the level of confidence in these trends (Supplementary material). However, another convincing line of evidence is derived from the knowledge that sugarcane yields (tonnes per hectare harvested) have been consistent for the past 50 years (Fig. 6) which is supported by independent industry datasets (Supp. Figs. 60–71). This finding, coupled with the reduced district-average N fertiliser application rates (high confidence data) over the past one to two decades (Fig. 7a), clearly highlight improvements in N fertiliser management. Hence, we can conclude that N use efficiency in the sugarcane industry is the most efficient it has been in 50 years.

4. Discussion

4.1. Basin and NRM scale data trends

Spatial time series compilations of fertiliser N and P application provide an invaluable resource to evaluate trends over time and help inform decision making and policy development in the context of crop management, protection of water resources, food security and climate change (e.g. Borbor-Cordova et al., 2006; Hamlin et al., 2020; Coello et al., 2025). Our compilation offers an evaluation of trends in N and P fertiliser application at both the river basin and NRM region scale. The trends in our data such as the steep increase in application from the 1960s and 1970s are broadly consistent with those reported from USA catchments (Howarth et al., 2002; Cao et al., 2018). Hence, these findings likely reflect the trends across the global agricultural sector with the increasing availability, affordability and reliance on N fertiliser from the ~1960s (e.g. Smil, 2001; Galloway et al., 2004; Kuhn, 2026). The widespread decline in fertiliser application over the past one to two

decades (Figs. 3 and 4) reflects a combination of improved farm management practices, increased knowledge extension to farmers, government regulation of fertiliser application rates, changing land use/cropping type and increasing costs of fertiliser.

The quantities of N and P fertiliser applied in sugarcane have declined considerably between the 1990 and 2024 periods in the Wet Tropics, Mackay Whitsunday and Burnett Mary NRM regions (Fig. 4). This is explained by reduced fertiliser application rates in the Wet Tropics and Mackay Whitsunday NRM regions (i.e. the sugarcane fertilised areas are similar over the two periods), and a marked reduction in sugarcane area coupled with reduced application rates in the Burnett Mary NRM region. In contrast, the N and P fertiliser quantities applied in bananas in the Wet Tropics, cotton in the Fitzroy and fruit and nuts (macadamias) in the Burnett Mary have increased from 1990 to 2024 due to considerable industry expansion (Fig. 4).

At the finer river basin scale, the data responds to intricate changes in land use, cropping area, fertiliser rate and crop type. These changes are evident in the basin profiles presented in Supplementary Tables 2 and 3 and Supplementary Figs. 1–29 which highlight the change in the amount and proportion of N and P fertiliser applied across the seven crop groupings between 1990 and 2024 (see also Supp. Figs. 31–59 for full N and P time series from 1910 to 2024). For example, the total amount of N fertiliser applied in the Russell Mulgrave Basin has halved over this period (Supp. Fig. 35) primarily due to a decline in sugarcane area at the expense of urban growth – the human resident population in this basin has doubled over the same period (see Lewis et al., 2021). We note that our compilation does not take into account the extra N and P that would be associated with the urban development. For basins such as the Herbert, O'Connell and Plane where the area of sugarcane has been relatively consistent over 30 years, the reduction in N fertiliser reflects reduced application rates in sugarcane (Supp. Figs. 9, 16, 18). The increases in fertiliser use in the Houghton and Burdekin Basins reflect the increased cropping area following the construction of the Burdekin Falls Dam in 1987 (Supp. Figs. 12–13).

The construction of basin-scale time series of N and P fertiliser application along with productivity measures of yield and nutrient use efficiency provides a foundational record to document changing management in the agricultural sector as well as to understand the environmental history of GBR river basins. However, confidence in the accuracy of such records requires careful evaluation. Unfortunately, the fertiliser sales data which formed the basis of Pulsford's (1996) earlier compilation are not available over the more recent ~35-year period. Hence, the accuracy of our compilation is dependent on reliable annual data of fertilised cropping area and reliable data on average N and P fertiliser application rates for each of the crop groupings.

We have undertaken various data validation and cross-checking exercises (see Supp. Material overview) to examine the accuracy of our reconstruction (see also Fig. 2). These checks include comparisons with independent data on sugarcane cropping area, sugarcane yield and crop fertiliser application rate data as well as ABS fertiliser product application data from the 2001 survey. These comparisons demonstrate a high level of confidence in the reconstructed cropping areas, sugarcane yields and sugarcane fertiliser application rates which support our approach. However, our 2001 N and P fertiliser application data differ from the corresponding 2001 ABS fertiliser application data for that year (discussed in the Supp. Material overview). Additional independent validation data, which are not currently available, would be required to provide a further check of our reconstructed values.

4.2. Fertiliser additives

The application of mill mud/ash on sugarcane paddocks has been shown to benefit soil health with additions of organic carbon and nutrients to fuel the microbial community and enhance nutrient cycling (Liu et al., 2021), although nutrient contents need to be considered to avoid the over-fertilisation of crops (Qureshi et al., 2007; Moody and

Schroeder, 2014; Thorburn et al., 2024). The use of mill mud/ash in the sugarcane industry provides an effective and innovative approach to recycle and dispose this milling by-product (Qureshi et al., 2007). The ABS, 2010 provide estimates of the amounts of mill mud/ash and animal manure applied in the GBR river basins for the 2008/09 season whereby the amounts of plant-available N and P can be calculated (Tables 5 and 6). Our data show that, on a basin-scale, mill mud/ash contributes up to 10% additional plant available N (Table 5) and up to 60% to 150% of extra plant available P (Table 6) applied on top of synthetic fertiliser. Hence, the application of P in mill mud/ash represents a considerable addition at a farm-scale, and reliable annual application amounts of mill mud/ash are required to develop farm-scale N and P budgets (with the redistribution of N and P needing to be recognised in any basin-scale nutrient budgeting). It is currently an industry recommendation (and regulatory requirement) that farmers take into account, and adjust for, mill by-product nutrient content for applications >100 wet tonnes/hectare. Mill mud/ash is commonly locally applied at ~100 wet tonnes per hectare and, at this rate, N and P application rates associated with sugar mill by-products equate to between 140 and 300 kg ha⁻¹ of N and 130 to 370 kg ha⁻¹ of P (P. Larsen and G. Shannon, pers comm, 2026). However, these rates do not reflect the plant-available N and P to the crop; a mineralisation study of mill mud/ash shows that the proportion of the total N immediately available (i.e. within 1 year of application) to the plant is highly variable (16 to 33%) across the sugar mills which reflect the quality of the mud/ash (Soil, Catchment and Riverine Processes, 2023). Note, these values are lower than that earlier reported by Moody and Schroeder (2014), who found 50% plant-available N in mill mud. Hence, additional synthetic N and P fertiliser inputs may still be required following the application of mill mud/ash on a paddock. Paddock-scale water quality trials show elevated dissolved inorganic P concentrations leaving paddocks following the addition of surface-applied mill mud (Armour et al., 2022).

In contrast, the ABS, 2010 data suggest that the application of animal manure provides a relatively limited amount of plant-available N and P on paddocks (Tables 5 and 6). Animal manure is likely to improve soil health and is an effective way to recycle and dispose of this material in the grazing industry.

The addition of N from legume crops grown in the fallow stage of the sugarcane cropping cycle has not been considered in this compilation but remains critical to incorporate into farm nutrient budgets and also likely basin-scale budgets. For example, Park et al. (2010) demonstrated that a soybean legume crop can contribute 300 kg ha⁻¹ of available N to the plant crop with a reducing proportion of N from this legume crop available up to the 4th ratoon crop; although subsequent studies have questioned the availability of the legume N to the crop in the ratoon stages (Salter et al., 2019). Legume crops not only provide a valuable nutrient addition to the soil, they also improve soil health, break crop monocultures, reduce pest/disease risks, and offer potential income stream diversification (Garside and Bell, 2007).

4.3. Other natural and anthropogenic sources of N and P

Other natural and anthropogenic sources of N and P should be considered to develop complete basin-scale nutrient budgets. These include inputs from urban and industrial uses, sewage treatment plant discharges, animal excrement including dogs in urban settings and cattle on grazing lands as well as atmospheric deposition. We note these inputs have not been considered in our compilation. These additions are locally important but are, in many cases, clearly more difficult to quantify. Indeed, research that considers the complete mass balance of nutrients in landscapes are rare but provide critical information on the contributions of different land uses and the dominant processes that add, transform and remove N and P (e.g. Borbor-Cordova et al., 2006; Hamlin et al., 2020; Karimi et al., 2020).

4.4. Fertiliser and farm management

While a number of factors can affect sugarcane yield and nutrient use efficiency such as climate, soils, and fertiliser management, optimising N application rates and fallow management is considered the highest priority in the GBRCA (Thorburn et al., 2017; 2022, 2024). The Burdekin NRM region produces the highest sugarcane yields (average: 110 t ha^{-1}) compared to the other sugarcane producing regions (75 to 78 t ha^{-1}) due to the abundance of water (under furrow irrigation) and sunlight (Fig. 6) (Davis et al., 2014; Thorburn et al., 2022). As such, the Burdekin NRM region has the highest N application rates in sugarcane compared to the other regions which are under a mix of rainfed and supplemental irrigation. The reported sugarcane yield data for the Burdekin Mills (Sugar Research Australia, 2025) are consistently in the order of 10 t ha^{-1} higher than yields calculated for the Burdekin and Haughton Basins using the ABS data. We cannot explain this discrepancy, although we note these numbers are within the uncertainty bounds used in this study (i.e. sugarcane production and land use area have uncertainties of $\pm 10\%$ each); indeed, the long-term average (1990–2021) from the Burdekin Mills is 115 t ha^{-1} (Sugar Research Australia, 2021) which falls in between our estimates and the recent Sugar Research Australia data. Yields over the past 40 years have varied from year-to-year likely in response to annual variability in rainfall and incidences of disease while longer term trends may be influenced by climate variability, improved sugarcane varieties, industry expansion on virgin lands (i.e. soils with higher organic carbon), irrigation expansion and improved pest/disease controls. Importantly, despite the industry perceiving a yield decline in the 1990's (Garside et al., 2005), we have found no major trend in yield over this 40-year period (Fig. 6) and the yields are consistent with those reported from the mills over 1990–2022 (Sugar Research Australia, 2021; Supp. Figs. 60–71). The year-to-year variability in productivity and nutrient use efficiency also likely provide a reflection on changing fertiliser costs, sugar price, and the success of the previous season in terms of harvested area and timing (Garside et al., 2014). The anomalous years with reduced harvests, yields and low N use efficiency often follow years with high sugarcane standover following a wetter than average year or a major cyclone. For example, several regions recorded low productivity in 1992 and 2012, which followed years of high rainfall (1991 and 2011) and Tropical Cyclone Yasi (February, 2011).

Our compilation reveals that farmers are making considerable strides in improved management of synthetic N and P fertiliser application in the river basins of the GBRCA. In 2016, nutrient application rates in the sugarcane industry were in-line with recommended management practice, as outlined by the “Six Easy Steps” soil-specific nutrient management guidelines for sugarcane production (Incitec Pivot, 2018). The application of N and P have reduced markedly over the past one to two decades in some river basins to the extent that reductions in catchment loads of N (and possibly P) should become apparent in water quality monitoring programs where long-term data are available. Indeed, trend evaluation of long-term monitoring data across several rivers of the GBRCA show that DIN concentrations have declined over the past decade which often coincide with decreasing synthetic N fertiliser application (James et al., 2026). Basin-scale monitoring data of waterways draining different areas of upstream fertilised land use show a strong positive relationship between DIN concentration and increased cropping area (Hunter and Walton, 2008; Bainbridge et al., 2009; Mitchell et al., 2009). Hence, reductions in river DIN loads would be expected for some basins and this compilation provides another line of evidence to help interpret trends in future analysis of water quality datasets.

The N and P time series also provides a foundational dataset to model reductions of river basin nutrient loads. In fact, the earlier reductions in N and P application achieved for some basins such as the Herbert in the early 2000s would not have been captured within the Reef Plan (2024) report cards which were initially benchmarked at the 2009 baseline

management scenario. We note that the dynamic SedNet model simulates loads over a 30 year climate period under static land use with annual changes in catchment condition, land use practices and on-ground remediation activities to quantify load reductions (McCloskey et al., 2017, 2021). Hence the reductions in synthetic N and P fertiliser application cannot be directly compared and do not necessarily translate to reductions in loads as reported by the model.

These earlier reductions in N and P fertiliser application reflect a combination of economic, climatic, social and policy drivers. Economic influences include fluctuations in fertiliser input costs and sugar prices. At local to regional scales, climatic disturbances such as cyclones and flooding also affect application patterns. Differences in farm demographics likely also contribute, with farms in the Wet Tropics often characterised by small family-run operations while those in the Burdekin and Mackay Whitsunday NRM regions are dominated by larger corporate farms. In addition, policy initiatives such as the Sugar Infrastructure Package (which included increased education on fertiliser management) and increased awareness of water quality issues following the commencement of the Reef Water Quality Protection Plan in 2003 may have influenced management practices. It is beyond the scope of this compilation exercise to examine these potential drivers. While sugarcane farmers have clearly reduced overall synthetic fertiliser application rates, data suggest there is still room for improvement in accounting for N and P surpluses at the paddock scale (i.e. from legume and mill mud inputs). The 2019 Report Card (Reef Plan, 2024) – the most recent to report on management practices – suggests that producers were a considerable way off achieving the target of 90% of sugarcane area under best management practice systems. The low adoption rates to reduce off-farm nutrient losses have largely been linked to the limited perceived or real benefits of implementing new practices in terms of improved productivity, profitability, convenience and risk exposure as well as limited access to skilled extension support (State of Queensland, 2025).

The development of crop-specific nutrient budgets has been increasingly used to evaluate the performance of the agricultural industry through nutrient use efficiency measures (e.g. Lu et al., 2019; Karimi et al., 2020; Xia et al., 2021; Zhang et al., 2021; Thorburn et al., 2022). Our data indicate that nutrient use efficiency in the Queensland, Australia sugarcane industry (Fig. 7) is the best it has been in 50 years, while the yields have remained consistent over this time (Fig. 6). These results are consistent with industry sources and supported by independent studies examining other benefits of improved nutrient use efficiency such as reduced greenhouse gas emissions (Renouf et al., 2024). Our nitrogen use efficiency estimates also closely match those reported by (Thorburn et al. (2022) who termed the kg N t^{-1} cane produced as the Nitrogen Loss Reduction Index (NLR). This improvement in efficiency is testament to the efforts of the Reef Plan program (and farmers themselves) through improved education and training available to farmers, access to better equipment to apply fertilisers, enhanced extension support and regulation as well as the willingness of some farmers to trial and adopt improved management practices (Eberhard et al., 2021).

The basin-averaged N fertiliser application rates appear to meet the district yield potential rates within the regulated Six Easy Steps guidelines (Fig. 7a) in agreement with Incitec Pivot (2018) reporting. There are a range of options currently being trialled to further improve nutrient use efficiency in the sugarcane industry such as the use of enhanced efficiency fertilisers, multiple species cover crops grown in the fallow and better accounting for farm nutrient budgets, although these trials need further testing across a variety of climate and soil types (Thorburn et al., 2024). While a large focus of the research has traditionally been on N management, the sugarcane industry are also looking to address other productivity constraints to improve nutrient use efficiency such as crop disease control, soil health and macro- and micro-nutrients (S. Clarke pers comm, 2025). Indeed, with N fertiliser rates around recommended industry benchmarks, new innovations to

reduce paddock N losses or to capture and treat runoff water are likely needed to achieve water quality targets (Waterhouse et al., 2026).

The sugarcane industry has been a mainstay within the GBRCA since the mid-1860s and has been resilient to changes in farming systems and shown innovation towards changing management practices including green cane trash blanketing, fertiliser types and application methods and pesticide regulation and management (Wood, 1991; Prove et al., 1995; Johnson and Ebert, 2000; Griggs, 2011; Lewis et al., 2021; Kuhn, 2026). While there are ongoing challenges for the agricultural industry to further manage fertiliser and pesticide losses from farms, our data highlight the encouraging signs that management efforts are delivering a measurable improvement in fertiliser use efficiency.

5. Conclusions

This manuscript constructs a foundational record of synthetic N and P fertiliser application in the basins of the GBRCA to help evaluate (or attribute causation) trends in water quality, assess nutrient management, agricultural sustainability and regional planning. The data show considerable reductions in the synthetic N and P fertiliser applied in most river basins of the GBRCA over the past one to two decades coupled with improvements in nutrient use efficiency while maintaining crop yields. There are less data on the amount of N and P added to crops through applications of mill mud/ash, animal manure and legume crops grown and ploughed in during crop fallows. Accounting for these additional contributions will be critical to develop N and P mass balances for cropping systems as well as to construct basin-scale N and P budgets.

The accuracy of the compilation was dependent on reliable annual fertilised cropping areas coupled with corresponding fertiliser application rates for the various crop groupings. The compilation has the highest confidence at the broader NRM scale and for basins where N and P inputs are dominated by sugarcane, bananas and cotton due to the temporal availability of accurate average application rates. In parallel with productivity data, the N and P application rates provide insights on improvements in management and nutrient use efficiency. This compilation provides a foundation for future studies to perform a mass balance of N and P used in cropping systems including fertiliser uptake, transformations and losses.

The reconstruction could be further strengthened through access to fertiliser sales data, improved knowledge on regional/local fertiliser application rates and greater clarity in future agricultural census reporting. If all industries reported district-average fertiliser application rate data—as the cotton industry currently does—it would enable similar analyses to be conducted in the future with considerably less effort and provide greater accuracy. Should reliable basin-scale N and P fertiliser application data become available in the future, the outputs of this study could be further refined to produce a compilation with reduced uncertainty. A more thorough repository of N and P application at the basin scale which incorporates additional N and P inputs such as through sewage treatment plant releases, urban runoff, industrial releases and grazing animal inputs would further enhance nutrient budgets and nutrient modelling for the GBRCA.

Future studies should use this compilation as a line of evidence to evaluate and explain trends in water quality data from the GBR rivers, examine its application to model changes in N and P loads to the GBR lagoon and help develop an annual repository of fertiliser application to benchmark and document trends into the future. The methodology developed in this study could be applied internationally to construct similar time series of basin-level fertiliser use to assess management practice changes, crop fertiliser use efficiency, determine environment impacts and evaluate ecological pressures.

CRedit authorship contribution statement

Stephen E. Lewis: Conceptualization, Data curation, Formal

analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Cassandra S. James:** Formal analysis, Methodology, Visualization, Writing – review & editing. **Zoe T. Bainbridge:** Conceptualization, Funding acquisition, Methodology, Project administration, Visualization, Writing – review & editing. **Aaron M. Davis:** Conceptualization, Formal analysis, Methodology, Writing – review & editing. **Adam Northey:** Conceptualization, Methodology, Resources, Writing – review & editing. **Emma Lawrence:** Formal analysis, Methodology, Validation, Writing – review & editing. **Rebecca Bartley:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.130679>.

Data availability

Data will be made available on request.

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