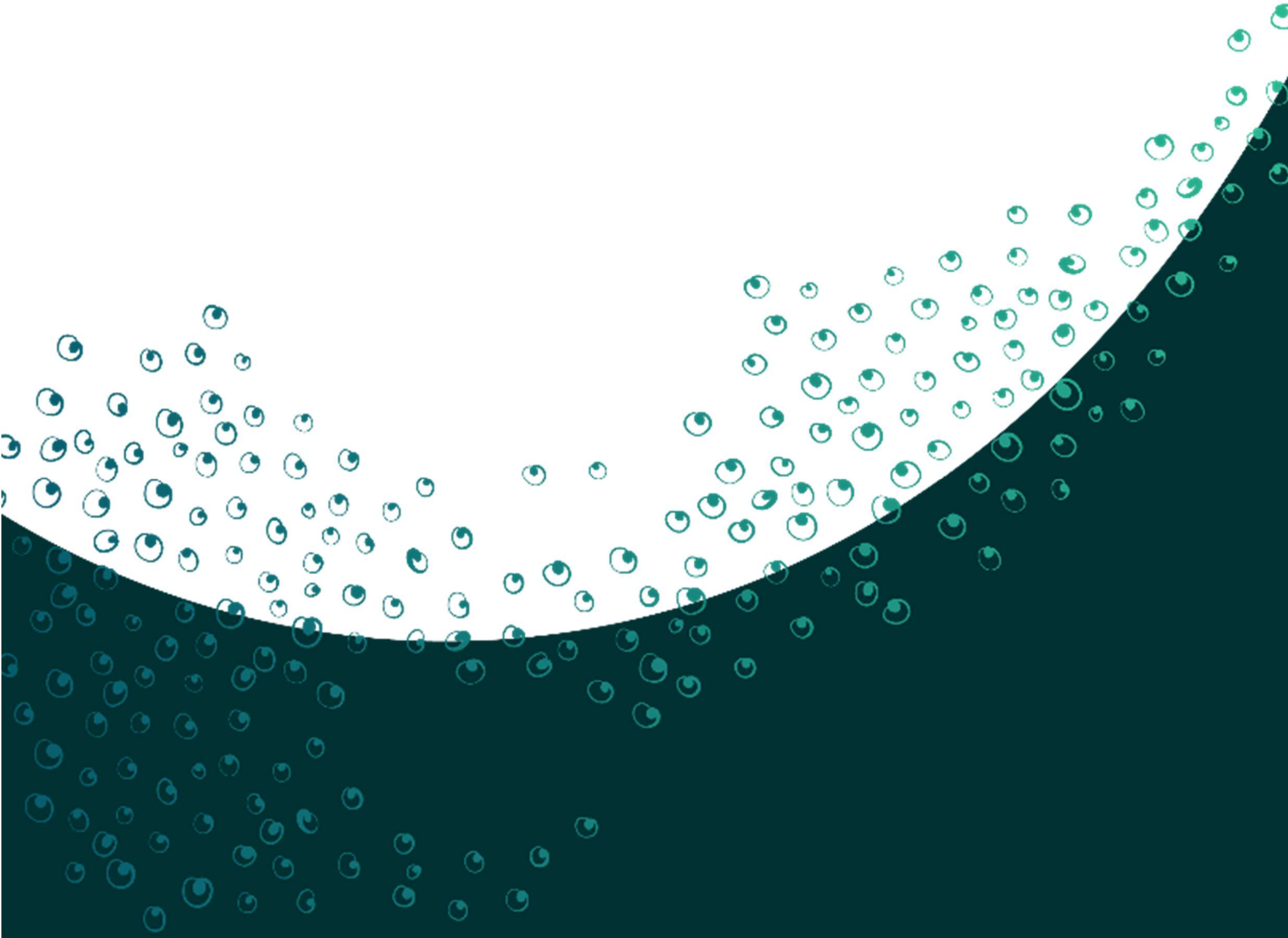

RP240

Improving knowledge and research for horticulture and cropping activities

Queensland
Government

Prepared by: Landscape Sciences, Soil Catchment and Riverine Processes Group, Department of Environment and Science

© State of Queensland, 2022.

The Department of Environment and Science acknowledges Aboriginal peoples and Torres Strait Islander peoples as the Traditional Owners and custodians of the land. We recognise their connection to land, sea and community, and pay our respects to Elders past, present and emerging.

The department is committed to respecting, protecting and promoting human rights, and our obligations under the Human Rights Act 2019.

The Queensland Government supports and encourages the dissemination and exchange of its information. This work is licensed under a Creative Commons Attribution 4.0 International License.

Under this licence you are free, without having to seek our permission, to use this publication in accordance with the licence terms. You must keep intact the copyright notice and attribute the State of Queensland as the source of the publication.

For more information on this licence, visit https://creativecommons.org/licenses/by/4.0/

Disclaimer

This document has been prepared with care, based on the best available information at the time of publication. The department holds no responsibility for any errors or omissions within this document. Any decisions made by other parties based on this document are solely the responsibility of those parties. Information contained in this document is from a number of sources and, as such, does not necessarily represent government or departmental policy.

If you need to access this document in a language other than English, please call the Translating and Interpreting Service (TIS National) on 131 450 and ask them to telephone Library Services on +61 7 3170 5470.

This publication can be made available in an alternative format (e.g. large print or audiotape) on request for people with vision impairment; phone +61 7 3170 5470 or email <library@des.qld.gov.au>.

Citation

Soil, Catchment and Riverine Processes Group. 2022. RP240: Improving knowledge and research for horticulture and cropping activities. Brisbane: Department of Environment and Science, Queensland Government.

Acknowledgements

Department of Environment and Science Queensland Reef Water Quality Program and Landscape Sciences branch are jointly acknowledged for their support of this project. The authors thank Dr Yash Dang, University of Queensland and Dr Michael Newham, Department of Environment and Science, for their independent review and feedback following drafting of the report.

Version 1.0

Abbreviations

ABS	Australian Bureau of Statistics
ABGC	Australian Banana Growers Council
a.i.	Active ingredient
ALUM	Australian Land Use Mapping
ANZECC	Australian and New Zealand Environment and Conservation Council
APVMA	Australian Pesticides and Veterinary Medicines Authority
ATCM	Australian Tree Crop Map
BMP	Best Management Practice
Ca	Calcium
CRDC	Cotton Research and Development Corporation
CT	Conventional tilling
Cu	Copper
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
EMC	Event mean concentrations
FAO	Food and Agriculture Organisation of the United Nations
FRP	Filterable Reactive Phosphorus
GBR	Great Barrier Reef
GM	Genetically modified
GPWUI	Gross Production Water Use Index
GRDC	Grains Research & Development Corporation
GPS	Global Positioning System
IPDM	Integrated Pest and Disease Management
IPM	Integrated Pest Management
IWUI	Irrigation Water Use Index
K	Potassium
Mg	Magnesium
N	Nitrogen
NH_3	Ammonia
NOx-N	Nitrogen oxides
NRM	Natural Resource Management
NUE	Nitrogen Use Efficiency
P	Phosphorus
PP	Particulate phosphorus
PAM	Polyacrylamide
PIN	Particulate inorganic nitrogen

PON	Particulate Organic Nitrogen
QDAF	Queensland Department of Agriculture and Fisheries
QG	Queensland Government
QLUMP	Queensland Land Use Mapping Program
RSE	Relative standard error
R&D	Research and Development
RT	Reduced till
S	Sulphur
SS	Suspended Sediment
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
WFIE	Whole Farm Irrigation Efficiency
WUE	Water Use Efficiency
Zn	Zinc

Commodities and regions in scope: summary table

In scope	Out of scope
Regions within the Great Barrier Reef Catchment: Burnett Mary Fitzroy Mackay Whitsunday Burdekin Wet Tropics Cape York	Regions outside of the Great Barrier Reef Catchment
Commodities^:	**Commodities^:**
Dryland: Cereals, Pulses *Sorghum* *Wheat* *Pulses*	Dryland (excluding cereals, pulses): Beverage & Spice crops, Hay and Silage, Oilseed, Sugar, Cotton, Alkaloid Poppies, Tree Fruits, Olives, Tree nuts, Vine Fruits, Shrub berries and fruits, Perennial flowers and bulbs, Perennial vegetables and herbs, Citrus, Grapes, Seasonal fruits, Seasonal flowers and bulbs, seasonal flowers and herbs.
Irrigated: Cotton, Tree Fruits, Tree Nuts, Perennial Vegetables, Fruit & Nut Crops *Cotton* *Bananas* *Macadamias* *Avocados* *Vegetables* *Pineapples*	Irrigated: Cereals, Beverage and spice crops, Hay and Silage, Oilseeds, Sugar, Alkaloid poppies, Rice, Olives, Vine fruits, Shrub berries and fruits, Perennial flowers and bulbs, Perennial herbs, Citrus, Grapes, Seasonal fruits, Seasonal flowers and bulbs, Seasonal vegetables and herbs, Turf farming

^based upon Australian Land Use and Management and Australian Bureau of Statistics Classification schema

Executive Summary

The Great Barrier Reef (GBR) catchment contains 997,948 ha (2.33% of the catchment area) of horticulture and cropping (excluding sugarcane) land which, like all agriculture, has the potential to impact offsite water quality including the GBR lagoon. Information regarding the extent that commodity-specific activities potentially impact offsite water quality is periodically updated to inform the design and implementation of on-ground actions within GBR catchment regions, as well as assist with program and policy decisions. This report finds, collates and qualitatively synthesises existing knowledge of measured losses of water, sediments, nutrients and pesticides from horticulture and cropping (excluding sugarcane) within the GBR catchment, and identifies the present gaps in knowledge that require further consideration.

In-scope classifications from the Australian Land Use and Management classification, as determined by the Office of the Great Barrier Reef, were dryland and irrigated cropping, dryland and irrigated perennial horticulture and dryland and irrigated seasonal horticulture. These were refined further by considering the spatial extent of commodities across the GBR catchment, consisting of six NRM regions, namely Burnett Mary, Fitzroy, Mackay Whitsunday, Burdekin, Wet Tropics and Cape York, as well as prioritising commodities with existing research underway. Following this refinement activity, commodity classes identified to focus the knowledge gaps synthesis included: cereals and pulses, irrigated cotton, bananas, macadamias, avocados, vegetables, and pineapples. A targeted search of scientific journals and published literature including industry, government, regional bodies and non-government databases was conducted. This included a literature search of publicly available information and datasets according to criteria including industry background, as well as available information relating to water, sediments, nutrients and pesticides within the GBR catchment regions. Information was then synthesised according to available evidence to inform of knowledge gaps for future consideration.

Overall, a widespread scarcity of published data on losses of water, sediments, nutrients and pesticides from horticulture and cropping (excluding sugarcane) in the GBR catchment was identified. Of the commodities assessed, bananas and cereals had the largest number of datasets and sites reporting offsite losses, while avocados, macadamias and vegetables had the least. More measurements of losses from systems in the GBR catchment are required, as many of the management practices which impact offsite losses are specific to commodities and therefore cannot be reliably inferred from other crops which are more widely studied in the GBR catchment.

Out of the four loss categories assessed (i.e. water, sediments, nutrients and pesticides) pesticides had the least amount of information available, including information on the type and quantity of pesticides applied to crops. Similarly, nutrient input data were not readily available for many commodities. Inadequate data on inputs into these agricultural systems provide a significant barrier to further assessment of the potential for offsite water quality impacts from these systems. Consistent measurements of pollutant losses and the reporting of consequent data, where possible, would assist in the comparison of data and interpretation across commodity classifications.

Specifically for the priority commodities:

Cereals and pulses – Longer term studies (>5 years) on pollutant losses from cereal and pulse cropping has greatly contributed to the knowledge base in this commodity class and provided important insights into loss pathways and temporal dynamics. These systems generally have low nutrient inputs but have still recorded notable offsite nutrient and sediment losses. The contribution of soil mineralisation, residue mineralisation and bioavailable nutrients (BAN) to offsite nutrient movement is a knowledge gap requiring attention.

Irrigated cotton – The majority of literature reporting losses from cotton were measured >20 years ago, indicating a potential knowledge gap regarding losses associated with current best management practices. Large inputs of water are required to grow cotton and have the potential to move pollutants off farm. Measurements have shown the potential for pollutant losses from paddock to natural waterways, however the recirculation of irrigation water on farm with respect to the movement of pollutants off farm under the current best management practice suggests a knowledge gap requiring research.

Bananas – Historically, large nutrient and water inputs (irrigation and rainfall) predispose banana cropping to potentially high pollutant losses. Reported measurements have shown high nutrient and sediment losses, but also the potential to decrease nutrient losses when efficiently managed. However, the limited loss measurements under newly regulated management practices across a variety of different site conditions remains a knowledge gap.

Macadamias – Available information regarding Macadamia orchards suggests that irrigation and fertigation practices may potentially minimise irrigation-linked pollutant losses. However, storm events still pose a risk of offsite movement of pollutants especially on steeper slopes and if inter-rows are bare. A knowledge gap exists regarding reporting of measured losses, as only one study measured pollutant losses in the GBR catchment. Measurements in higher rainfall areas of the catchment would also be important if pollutants are mainly linked to storm events.

Avocados – Available data suggests that efficient management practices (e.g. fertigation) are commonly adopted in the avocado industry and may mitigate losses However, in some instances, nutrient application rate as applied to orchards may be high, with sediment and nutrient losses accompanying intense storms likely. A large knowledge gap exists, with no measured data found on any pollutant losses from avocado orchards in the GBR catchment.

Pineapples –Erosion and sediment losses has been a research focus due to the steep and exposed sandy soils under pineapple land use; when coupled with potentially large fertiliser inputs and permeable soils this suggests that potential exists for a 'leaky' system, with offsite movements of nutrients and pesticides. However, data regarding nutrient and pesticide losses was limited, suggesting a large knowledge gap for this class.

Vegetables – The vegetable class is unique in that it contains many different crops grown under varying management practices (e.g. plastic mulch, fertigation, field crops, sprinkler irrigation etc.). Generally, large inputs of nutrients are required for one crop, and often multiple crops are sown on the same land annually, effectively creating significant annual inputs of nutrients. Limited data on fertiliser and pesticide inputs, including measured losses, was found, suggesting a large knowledge gap. The large array of crops and management regimes in this class means that a significant amount of research would need to be undertaken to effectively measure losses.

Knowledge gaps identified in this report can be used to inform and prioritise future policy and research directions for public good outcomes. It is recognised that this project represents a 'point-in-time' review activity and that further engagement with industry and stakeholders would be beneficial, to identify whether any concurrent activities (e.g. under review publications; experimental trials currently underway) could further inform the design and implementation of on-ground actions within GBR catchment regions.

Contents

Project rationale and objectives

The 2017 Scientific Consensus statement identified diffuse source pollution from agriculture as the main source of primary pollutants (nutrients, fine sediments and pesticides) from Great Barrier Reef Catchments, noting also that these pollutants pose a risk to Great Barrier Reef coastal and marine ecosystems (see Bartley et al., 2017 for dedicated review of this).

Dominant contributors for primary pollutants have been identified as sugarcane (dissolved inorganic N and pesticides) and grazing (fine sediments and particulate nutrient) land uses (Bartley et al., 2017; Waterhouse et al., 2017), however other intensive cropping systems may also contribute pollutants in some instances, and that research gaps remain.

The 2017 Scientific Consensus Statement recommended that “industries such as horticulture and broadacre cropping require further attention as they present an opportunity for cost-effective outcomes in short timeframes” (Waterhouse et al., 2017). Therefore, it is important that existing knowledge on water quality impacts from these commodities is assessed and knowledge gaps highlighted, as a first step towards enhancing the scientific basis underpinning water quality management decisions in these commodities.

This project aims to (1) curate existing information and knowledge according to the Australian Land Use and Management (ALUM) classifications as agreed in-scope by the Office of the Great Barrier Reef; (2) analyse new and additional information to identify knowledge gaps for in-scope classes in reef catchments; and (3) synthesise this information in a manner which can be utilised for forward-planning.

Project scope

Programs and supporting tools are provided by the Australian and Queensland governments and industry organisations to help grains and horticulture producers identify opportunities to improve farming practices and assist in making decisions about new, diversified or intensified agricultural activities, or related supply chain matters.

Foundational to these programs and tools is the evidence base and knowledge relating to on-ground management, including the design and implementation of policy and programs in the Great Barrier Reef (GBR) catchments. A component of this decision-making process is the synthesis of information (illustrated in the conceptual framework of Wyborn et al. 2018; Figure 1).

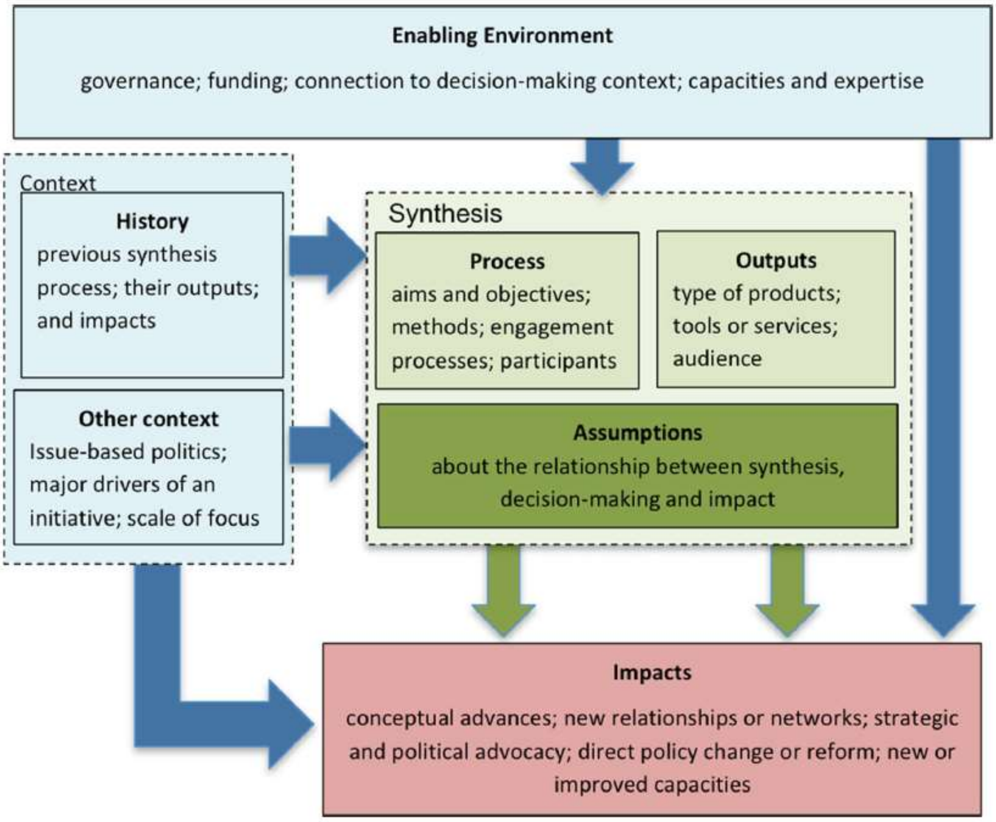

Figure 1. Conceptual framework of synthesis process and impacts, arrows indicate influence (Wyborn et al. 2018). The authors note that there are several models for impactful synthesis, reflecting the varying institutional arrangements, governance models, research and engagement processes.

This project applied a rapid knowledge gaps assessment approach in the form of a qualitative synthesis to:

- curate existing information and knowledge according to Australian Land Use and Management (ALUM) classification, aggregated to grouped commodity classes as agreed in-scope by the Office of the Great Barrier Reef;
- analyse new and additional information to identify knowledge gaps for in-scope commodity classes in reef catchments; and
- synthesise this information in a manner which can be utilised for forward-planning.

Horticulture and cropping classification approach

The land areas considered in the scope of this report are the six NRM regions which drain into the GBR. These are Burnett Mary, Fitzroy, Mackay Whitsunday, Burdekin, Wet Tropics and Cape York. The crop classes initially considered in this report are limited to the ALUM classes in Table 1 as determined by the Office of the Great Barrier Reef. Sugar and irrigated sugar classes usually fall under the cropping and irrigated cropping classes, respectively, in ALUM, although the Office of the Great Barrier Reef considered them as out of scope for this activity. Within each tertiary ALUM class there are generally multiple commodity classes. These initial ALUM classes were further focussed to priority in-scope classes in the following section using available spatial information and a defined criteria as outlined in “Summary of classes featured in this report”. A detailed list of commodity classes linked to each tertiary class are outlined in Appendix 1.

Table 1 Primary, Secondary and Tertiary Australian Land Use and Management Classification (ALUM) classes included in the scope of this report

3.0 Production from dryland agriculture and plantations		4.0 Production from irrigated agriculture and plantations	
3.3.0	Cropping	4.3.0	Irrigated Cropping
3.3.1	Cereals	4.3.1	Irrigated Cereals
3.3.2	Beverage and Spice crops	4.3.2	Irrigated Beverage and Spice crops
3.3.3	Hay and silage	4.3.3	Irrigated Hay and silage
3.3.4	Oilseeds	4.3.4	Irrigated Oilseeds
3.3.6	Cotton	4.3.6	Irrigated Cotton
3.3.7	Alkaloid poppies	4.3.7	Irrigated alkaloid poppies
3.3.8	Pulses	4.3.8	Irrigated Pulses
		4.3.9	Irrigated rice
3.4.0	Perennial horticulture	4.4.0	Irrigated Perennial horticulture
3.4.1	Tree Fruits	4.4.1	Irrigated Tree Fruits
3.4.2	Olives	4.4.2	Irrigated Olives
3.4.3	Tree nuts	4.4.3	Irrigated Tree nuts
3.4.4	Vine fruits	4.4.4	Irrigated Vine fruits
3.4.5	Shrub berries and fruits	4.4.5	Irrigated Shrub berries and fruits
3.4.6	Perennial flowers and bulbs	4.4.6	Irrigated Perennial flowers and bulbs
3.4.7	Perennial vegetables and herbs	4.4.7	Irrigated Perennial vegetables and herbs
3.4.8	Citrus	4.4.8	Irrigated Citrus
3.4.9	Grapes	4.4.9	Irrigated Grapes
3.5.0	Seasonal horticulture	4.5.0	Irrigated Seasonal horticulture
3.5.1	Seasonal fruits	4.5.1	Irrigated Seasonal fruits
3.5.2	Seasonal flowers and bulbs	4.5.2	Irrigated Seasonal flowers and bulbs
3.5.3	Seasonal vegetables and herbs	4.5.3	Irrigated Seasonal vegetables and herbs
		4.5.4	Irrigated turf farming

Queensland Land Use Mapping Program data

The Queensland Land Use Mapping Program (QLUMP) provides spatial data on the extent of specific agricultural classifications as outlined by ALUM for Queensland. The data is generated and maintained by the Queensland Government. The data is mapped to primary, secondary and where possible tertiary classifications. Furthermore, where tertiary classification has been mapped it may not be complete. This is evidenced from large areas still mapped to the secondary classification level (e.g. 3.3.0 cropping, 3.5.0 season horticulture etc.) in some areas. Some specific crops are reported to the commodity level including mangos, macadamias, avocados, bananas and pineapples, while cotton is considered its own tertiary class. The dataset, "Land use mapping – 1999 to current – Queensland", published 14 June 2019 was accessed from the Queensland Spatial Catalogue (QLUMP 2019). The currency of each NRM region's dataset was: Cape York, 2013; Wet Tropics, 2015; Mackay Whitsunday and Burdekin, 2016; Fitzroy and Burnett Mary, 2017.

Australian Bureau of Statistics data

The dataset "Agricultural commodities, Australia and state/territory and NRM regions - 2019–20" released 14 May 2021 contained agricultural commodity data including area (ha) cropped to a commodity and number of agricultural businesses growing a commodity within NRM regions (ABS 2021a). The dataset "Water use on Australian farms, Australia, state/territory and NRM and MDB regions - 2019–20" contained data on irrigation including area (ha) irrigated, volume (ML) applied, application rate (ML/ha) for commodity classes within NRM regions (ABS 2021b). Both datasets also included an estimate of the number businesses in each class. Not all commodity classes in the "Agricultural commodities, Australia and state/territory and NRM regions - 2019–20" dataset, were individually represented in the irrigation dataset but instead were aggregated together at a higher level.

The datasets were collated from a survey of businesses with an estimated value of agricultural operations of >$40,000. The response rate for the survey Australia wide was 78.4% from 25,642 agricultural businesses. As the data is obtained from a survey and not all participants responded to the survey a measure of sampling variability is the relative standard error (RSE). The RSE is the standard error as a percentage of the estimate. In situations where the estimates are small (i.e. only a small area cropped to a commodity, or a small number of businesses in a specified region), the RSE can be large. Further information on the methodologies used by the ABS to estimate agricultural commodities can be found on the ABS website. ABS data does not follow the ALUM classification scheme.

Australian Tree Crop Map data

Further commodity data was sourced from the Australian Tree Crop Map (ATCM) for macadamias, mangos, olives, avocados, citrus and bananas (Applied Agricultural Remote Sensing Centre 2021). The ATCM provides spatial data on the extent of these commodities across Australia. The ATCM is collated and maintained by the Applied Agricultural Remote Sensing Centre at the University of New England, with support from Hort Innovation and the individual commodity industries. Cropping is identified by remote sensing, ground-truthing and online submissions. Data was updated in January 2021.

Analysing data to define classes for knowledge gaps reporting

QLUMP data for Queensland was limited to the six NRM regions adjacent to the GBR by clipping the spatial data to the NRM region boundaries using the "natural resource management regional boundaries – Queensland" spatial layer, accessed from the Queensland Spatial Catalogue. The Cape York NRM boundary includes areas west of the Great Dividing Range, which does not drain into the GBR. Therefore, for the purposes of this report, Cape York NRM was considered only to the east of the Great Dividing Range. The resulting attribute table for each NRM region was then exported to Excel and the summed areas within each classification calculated. The area cropped to each classification was converted to hectares, before calculating the area cropped to a classification as a percentage of the total land area of a NRM region. These values were also calculated as a whole, for the six NRM regions. Area data is outlined in Appendix 1. The area mapped to sugar and irrigated sugar has been left in Appendix 1 for completeness. However, as sugar and irrigated sugar was consistently mapped to the tertiary level, it has been deducted from the secondary classes (cropping and irrigated cropping) to only show the extent of the classes that are within scope in Table 2.

Data from the ABS dataset "Agricultural commodities, Australia and state/territory and NRM regions (2019–2020) was sorted and limited to the six NRM regions adjacent to the GBR (as named in the ABS data), namely, Burnett Mary, Cape York, Fitzroy Basin, North Queensland Dry Tropics (Burdekin), Reef Catchments (Mackay Whitsunday) and Terrain NRM (Wet Tropics). The land area recorded as sugar production was deducted from the cereal crops and other crops class to calculate only crops within scope. In situations where data for an individual commodity class was recorded as not available for publication (np) and only one commodity from a total grouped commodity class was np, all other commodities were subtracted from the total grouped commodity to determine the area under the individual commodity recorded as np. If more than one commodity was listed as np within a total grouped class, then data was sourced from the previous two years where available. If data was not available in the previous two years, then the data was left blank. Therefore, in these cases, the summed area of each commodity will not equal the total recorded, as the data was not disaggregated from the aggregated class but will be included in the total aggregated class. It should be noted that the Cape York NRM region as defined by the ABS, includes basins draining West into the Gulf of Carpentaria and East into the GBR. However, to maintain the integrity and comparability to other datasets, the percent land area for a crop was calculated using only the land area which drains into the GBR. The total land area for the GBR NRM regions utilises only the land area draining into the GBR so as not to diminish the extent of crops across the whole GBR region. Since the Cape York NRM generally has less developed and less widespread agriculture this does not have a large impact on conclusions drawn.

Spatial data from the ATCM was separated into regions as previously discussed for QLUMP data.

Relative contribution – GBR and regions – defining classes applied to knowledge gaps review

Data, sourced from QLUMP, ABS and ATCM on the extent of in-scope agriculture within individual regions and across all regions are in Tables 2-7. Different data sources use different classifications and groupings. Figure 2 shows the linkages and commonalities between the classifications across data sources as presented in Tables 2-7 contained in Figure 2. For example, Tree crop data sourced from ATCM (Table 3), can fall under perennial or irrigated perennial horticulture in the ALUM classification used by QLUMP (Table 2), while beans in the ABS data (Table 7) is aggregated into vegetables (Table 4), which fits into either seasonal or irrigated seasonal horticulture in the ALUM classification (Table 2).

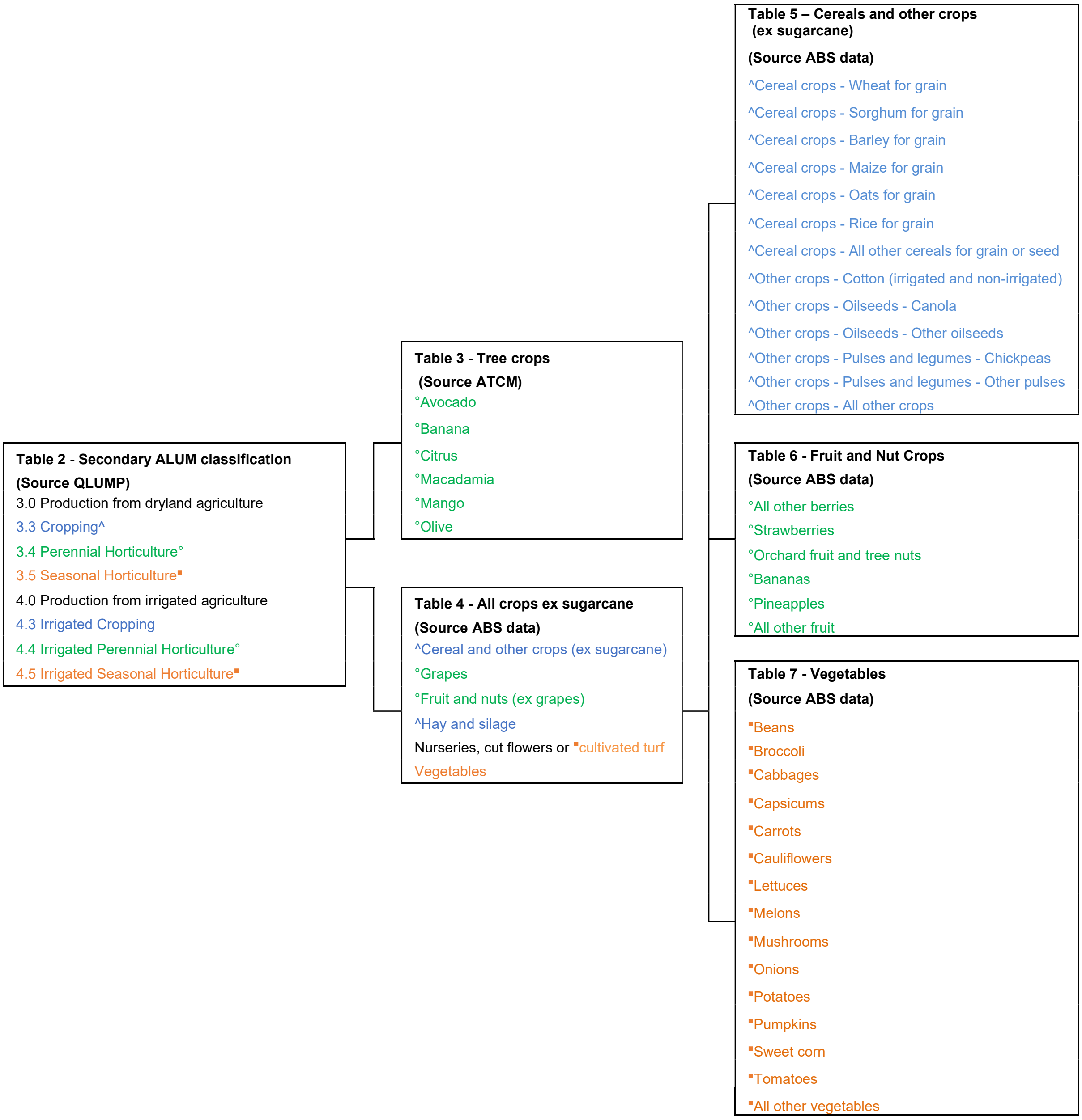

Figure 2 Linkages between classifications of different data sources. Classes with the same colour and symbol as an ALUM classification fall within that classification (Tables 2-7).

Spatial data – Entire Great Barrier Reef Catchment

Across all Great Barrier Reef NRM regions a total of 2.33% (997,948 ha) of the land area is within the scope of this report (Table 2). The majority of in-scope land is used for dryland cropping (1.78 %). In contrast perennial and seasonal horticulture is reliant on irrigation, with 0.19% of the total land area under irrigated horticulture compared to <0.01% under dryland horticulture.

Fitzroy has the largest land area cropped to dryland (559,791 ha) and irrigated cropping (93,152 ha), although the Burnett Mary has the largest percentage of land area devoted to irrigated cropping (0.69%) (Table 2). In comparison Mackay Whitsunday has only 0.07% of land area devoted to irrigated cropping and no dryland cropping. Burnett Mary has the largest area cropped to dryland (1,079 ha) and irrigated (25,010 ha) perennial horticulture, while the Wet Tropics has the largest percentage of land area cropped to irrigated perennial horticulture (0.92%).

Dryland and irrigated cropping ALUM classifications, and cereals & other crops and hay & silage as defined by the ABS include the same crops, so are comparable. According to ALUM classifications cropping covered 2.13% of the GBR NRM region (Table 2), while according to ABS data only 1.06% of the GBR region was covered by cereals & other crops plus hay & silage (Table 4). This discrepancy may be explained by the fact the data was collected in different years. Considering most of the cereals and other crops classification is dryland and weather dependent, there would likely be a significant contraction of dryland cropping during periods of drought. Hay and silage (irrigated and dryland), as classified in QLUMP data (Appendix 1) accounts for 0.02% of the GBR NRM region, in comparison ABS data indicates 0.12% or 50,963 ha of the GBR NRM region is cropped to hay and silage. This discrepancy is likely due to the secondary ALUM class of dryland or irrigated cropping, not being further disaggregated into the tertiary hay and silage classification in QLUMP data, which is a disadvantage of the tertiary classifications under ALUM. The composition of crop types that make up cereals and other crops is dominated by wheat, sorghum and pulses (Table 5). Together they account for 80% of the in-scope land area designated as cereals and other crops by the ABS (Table 5). Oats, maize and cotton were the next most widespread crops in this class. It should be noted that variability in cropping areas between years can be very high. The area cropped to cotton contracted by 44% in 2019–20 compared to the previous year. This occurred across the entire cotton industry and was driven by water scarcity. When the ABS data is compared to data from QLUMP the cotton area was reduced by 75% in 2019–20 (Appendix 1)

Tree crops including bananas accounted for up to 0.10% or 44,170 ha across the GBR NRM regions according to the ATCM (Table 3). Of those commodities included in the ATCM macadamias and bananas accounted for 30% and 28% of the tree crop area, respectively. Similar proportions were calculated from the QLUMP land use data (macadamia, 26%; bananas, 34%) (Appendix 1). Olives were the least widespread tree crop accounting for up to 1% of tree crops. Pineapples were grown on between 2,035–2,385 ha or <0.01% of the GBR NRM regions depending on the data source (Table 6; Appendix 1).

The ABS data indicates that land for vegetable production in the GBR NRM region is 0.04% of the total land area or 18,142 ha (Table 7), while QLUMP data suggests approximately half that amount (0.02%; 7,878 ha) (Appendix 1). However, in the QLUMP data, a large portion of land area has not been allocated from the secondary classification to the tertiary irrigated seasonal or perennial vegetable and herb classification, therefore the larger estimate from the ABS is likely to be more accurate in this case. From the 14 vegetables explicitly listed in the ABS data beans, sweet corn, melons (includes rock, bitter and water melons) and potatoes are the most widely planted vegetables in the GBR NRM regions, although a large proportion of vegetables are classified as 'other' (Table 7).

Overall, considering the available data identifying crop types the following in-scope crops are the most widespread across the six NRM regions: wheat, pulses, sorghum, cotton, vegetables, macadamias, bananas and avocados.

Spatial data – Burnett Mary

Cropping accounts for the largest percentage of in-scope agriculture in the Burnett Mary region covering 1.87% of the land area according to QLUMP data (Table 2). Sorghum, wheat and pulses are the main broadacre crops in the region, accounting for 21, 15 and 25% of cereals and other crops, respectively, according to ABS data (Table 5). Hay and silage, which is included in the dryland and irrigated cropping classification under QLUMP data, accounts for 0.37% (20,872 ha) of the Burnett Mary region according to ABS data (Table 4). Burnett Mary also has the largest percentage of land area under irrigated seasonal horticulture of the six regions (0.17%), with a large proportion of that being attributed to irrigated seasonal vegetables and herbs (Table 2; Appendix 1). Melons and potatoes are the most widespread vegetables grown, although a large proportion of data is recorded as 'other vegetables' in the ABS data (Table 7). Burnett Mary has the largest area under irrigated perennial horticulture of the six NRM regions, covering 25,010 ha (Table 2). Macadamia orchards make up the largest proportion of irrigated perennial horticulture accounting for 10,760 ha or 0.19% of the total land area, this is followed by citrus

(4,353 ha, 0.08%) and avocados (3,801 ha, 0.07%) according to QLUMP data (Appendix 1). Pineapples account for 0.02–0.03% of the land area depending on the data source, which is the largest percentage of all six regions (Appendix 1; Table 6).

Spatial data – Fitzroy

Fitzroy has the largest land area cropped to dryland (559,791 ha) and irrigated cropping (93,152 ha) amongst the six regions (Table 2). ABS data indicates that cereals and other crops is dominated by wheat, pulses and sorghum, which account for 34, 22 and 23%, respectively, of the area within cereals and other crops (Table 5). Fitzroy also contains the largest area under cotton cropping of the NRM regions according to both ABS and QLUMP data (Table 4; Appendix 1). The Fitzroy NRM has 0.15% or 23,159 ha cropped to hay and silage, which is the largest area out of the six NRM regions (Table 4).

Spatial data – Mackay Whitsunday

Mackay Whitsunday has the smallest area of agriculture land in scope of the six NRM regions (2,218 ha) which equates to 0.24% of its' area (Table 2). However, ABS data for 2019–20 indicates a larger area of in-scope agriculture. For instance, cereals and other crops alone made up 0.53% of the NRM region, followed by 0.17% for hay and silage (Table 4). QLUMP data indicates the region is heavily dominated by irrigated agriculture, with only 5% occurring via dryland, however this likely fluctuates depending on the crops grown and annual rainfall (Table 2).

Spatial data – Burdekin

The Burdekin has the second largest area under dryland cropping (132,677 ha) of the six NRM regions (Table 2). A breakdown of cropping by the ABS indicates that cereal and other crops is dominated by wheat, pulses and sorghum, which account for 39, 15 and 14% respectively of the cereals and other crops class (Table 5). Pulses, according to the ABS definition include chickpeas, faba beans, field peas for grain, lentils, lupins, mung beans, navy beans and peanuts. The Burdekin NRM has the largest area planted to mango orchards (3,044 ha, ATCM; 3,633 ha, QLUMP) of the six NRM regions and this is the main tree crop in the Burdekin (Table 3; Appendix 1). The Burdekin also has the largest area under irrigated seasonal vegetables and herbs (4,278 ha) as classified by QLUMP and vegetables (10,283 ha) as classified by the ABS, compared to other regions (Appendix 1; Table 4). A further breakdown of the vegetable types indicates that sweet corn, beans and melons account for 27, 26 and 14%, respectively, of the area under vegetable production, in the region (Table 7).

Spatial data – Wet Tropics

Irrigated perennial horticulture accounts for 66% of the in-scope agriculture within the Wet Tropics, which is the second largest by land area among the NRM regions (Table 2). This classification is dominated by bananas, which are grown on 0.65% (QLUMP) or 0.53% (ATCM) of the land area and is the main region where bananas are grown in Queensland (Appendix 1; Table 3). Avocados are the second most widespread tree crop in the region accounting for 0.11% (ATCM) or 0.05% (QLUMP) of the land area (Appendix 1; Table 3). Hay and silage according to ABS data accounts for 0.17% of the land area.

Spatial data – Cape York

Cape York has the lowest percentage of land attributed to in-scope agriculture of the six NRM regions (Table 2; 0.16%). 90% of in-scope land is attributed to the cropping classification, however a further breakdown to crop type could not be completed with confidence using the available data.

Summary of classes featured in this report

The previously identified classes in Table 1 were further focussed using the below criteria taking into account the spatial information presented above:

- (i) the extent of a class across all regions;
- (ii) the extent of a class within individual NRM regions;
- (iii) reporting to the commodity class level within QLUMP; and/or
- (iv) supporting current research underway for this commodity class.

This resulted in the following commodity classes being selected as in-scope commodity classes to be highlighted in the report:

ALUM 3.0 Production from dryland agriculture

Cereals – Sorghum; Wheat; Pulses	*widespread over multiple regions*

ALUM 4.0 Production from irrigated agriculture

Irrigated Cotton	*regionally widespread in the Fitzroy*
Bananas	*regionally widespread in the Wet Tropics*
Tree crops – Macadamias; Avocados	*regionally widespread in the Burnett Mary*
Vegetables	*regionally widespread in the Burnett Mary and Burdekin*
Pineapples	*commodity specified ‘in project scope.’*

Table 2 Land area cropped to secondary Australian Land Use and Management (ALUM) classifications in Natural Resource Management regions used in this report (QLUMP 2019).

Secondary ALUM Class	Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet tropics		Cape York		Total	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
3.0 Production from dryland agriculture														
3.3 Cropping§	65733	1.18	559791	3.56	0	0.00	132677	0.94	839	0.04	5229	0.12	764269	1.78
3.4 Perennial Horticulture	1079	0.02	29	<0.01	109	0.01	24	<0.01	62	<0.01	176	<0.01	1480	<0.01
3.5 Seasonal Horticulture	5	<0.01	0	0.00	0	0.00	0	0.00	6	<0.01	33	<0.01	44	<0.01
4.0 Production from irrigated agriculture														
4.3 Irrigated Cropping§	38581	0.69	93152	0.59	625	0.07	8223	0.06	8450	0.38	809	0.02	149839	0.35
4.4 Irrigated Perennial Horticulture	25010	0.45	6077	0.04	571	0.06	4796	0.03	20519	0.92	465	0.01	57439	0.13
4.5 Irrigated Seasonal Horticulture	9227	0.17	798	0.01	913	0.10	12779	0.09	1160	0.05	0	0.00	24876	0.06
Total	139636	2.50	659848	4.20	2218	0.24	158499	1.12	31036	1.40	6711	0.16	997948	2.33

§Values do not include land cropped to sugar or irrigated sugar.

Table 3 Land area cropped to tree crops in Natural Resource Management regions in the Great Barrier Reef catchment (Applied Agricultural Remote Sensing Centre 2021)^

Commodity	Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Total	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
Avocado	3938	0.07	26	<0.01	1	<0.01	9	<0.01	2492	0.11	63	<0.01	6530	0.02
Banana	91	<0.01	4	<0.01	9	<0.01	4	<0.01	11781	0.53	657	0.02	12546	0.03
Citrus	3723	0.07	1480	<0.01	6	<0.01	36	<0.01	445	0.02	0	0	5690	0.01
Macadamia	12695	0.23	459	<0.01	125	0.01	0	0.00	102	<0.01	0	0	13381	0.03
Mango	773	0.01	494	<0.01	146	0.02	3044	0.02	1040	0.05	18	<0.01	5515	0.01
Olive	498	<0.01	7	<0.01	0	0	3	<0.01	0	0	0	0	509	<0.01
Total	21718	0.39	2470	0.02	286	0.03	3097	0.02	15860	0.71	738	<0.01	44170	0.10

^Data sourced from the Australian Tree Crop Map.

Table 4 All crops in Natural Resource Management regions of the Great Barrier Reef catchment, as defined by the Australian Bureau of Statistics 2019-2020 (excluding sugarcane) (ABS 2021a).

Commodity	**Burnett Mary**			**Fitzroy**			**Mackay Whitsunday**			**Burdekin**			**Wet Tropics**			**Cape York**			**Total**	
	ha	RSE[#]	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	%
Cereals and other crops	28798	^	0.52	264704		1.68	4936		0.53	103563	^	0.74	1464		0.07	109	**	<0.01	403573	0.94
Grapes	322		<0.01	982		<0.01	-		-	-		-	-		-	-		-	1304	<0.01
Fruit and nuts (excluding grapes)	20724		0.37	1428		<0.01	65	^	<0.01	2272		0.02	16529		0.74	98		<0.01	41115	0.10
Hay and silage	20872	^	0.37	23159	^	0.15	1620	^	0.17	998	*	<0.01	4108	*	0.18	206		<0.01	50963	0.12
Nurseries, cut flowers or cultivated turf	420	*	<0.01	119	**	<0.01	100	^	0.01	66	**	<0.01	181	*	<0.01	-		-	886	<0.01
Vegetables	6665	^	0.12	123	**	<0.01	89		<0.01	10283		0.07	962	*	0.04	21		<0.01	18142	0.04
Total crops	77802		1.39	290513		1.85	6810		0.73	117181		0.83	23244		1.05	434	^	0.01	515983	1.20

[#]Relative Standard Error (RSE); ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%; ** estimate has a RSE greater than 50%. There are no calculated RSEs for row totals.

Table 5 Cereal and other crops in Natural Resource Management regions of the Great Barrier Reef catchment, as defined by the Australian Bureau of Statistics 2019-2020 (ex. sugarcane) (ABS 2021a).

Commodity	Burnett Mary			Fitzroy			Mackay Whitsunday			Burdekin			Wet Tropics			Cape York			Total	
	ha	RSE#	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	%
Cereal crops																				
- Wheat	4283	*	0.08	89374	^	0.57	707	**	0.08	38124	^	0.27	138	**	<0.01	-		-	132626	0.31
- Sorghum	6036	*	0.11	59578	^	0.38	953	**	0.10	20694	^	0.15	42	**	<0.01	109	**	<0.01	87412	0.20
- Barley	2455	*	0.04	4557	*	0.03	-		-	2106	*	0.01	-		-	-		-	9118	0.02
- Maize	4680	*	0.08	7088	^	0.05	552	**	0.06	436	*	<0.01	227	**	0.01	-		-	12983	0.03
- Oats	315	**	<0.01	15721	**	0.10	-		-	11	**	<0.01	52	**	<0.01	-		-	16099	0.04
- Rice	-		-	-		-	-		-	637		<0.01	-		-	-		-	637	<0.01
- Other	434	**	<0.01	486	**	<0.01	-		-	389	*	<0.01	-		-	-		-	1310	<0.01
Other crops																				
Cotton	239	*	<0.01	9791	^	0.06	-		-	53		<0.01	-		-	-		-	10083	0.02
Oilseeds - Canola	-		-	857		<0.01	-		-	-		-	3	**	<0.01	-		-	860	<0.01
Oilseeds - Other oilseeds	1357	*	0.02	199	**	<0.01	718	*	0.08	2763	^	0.02	-		-	-		-	5037	0.01
Pulses and legumes - Chickpeas	367	**	<0.01	59266	^	0.38	1812	**	0.19	36423	^	0.26	-		-	-		-	97868	0.23
Pulses and legumes - Other pulses	6891	*	0.12	17295	^	0.11	164	**	0.02	1926	*	0.01	361	*	0.02	-		-	26636	0.06
All other crops	1743	*	0.03	491	**	<0.01	31	**	<0.01	-		-	641	*	0.03	-		-	2905	<0.01
Total area	28798	^	0.52	264704		1.68	4936		0.53	103563	^	0.74	1464		0.07	109	**	<0.01	403573	0.94

#Relative Standard Error (RSE); ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%; ** estimate has a RSE greater than 50%. There are no calculated RSEs for row totals.

Table 6 Fruit and nut crops (excluding grapes) in Natural Resource Management regions of the Great Barrier Reef catchment, as defined by the Australian Bureau of Statistics 2019-2020 (ABS 2021a).

Commodity	**Burnett Mary**			**Fitzroy**			**Mackay Whitsunday**			**Burdekin**			**Wet Tropics**			**Cape York**			**Total**	
	ha	RSE[#]	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	%
Other berries	165		<0.01	-		-	1	*	<0.01	-		-	80	**	<0.01	-		-	246	<0.01
Strawberries	272		<0.01	-		-	5	*	<0.01	-		-	-		-	-		-	277	<0.01
Orchard fruit and tree nuts	18815		0.34	603		<0.01	24	*	<0.01	2153		0.02	4554	^	0.20	56		<0.01	26206	0.06
Bananas	26	^	<0.01	-		-	12	^	<0.01	2		<0.01	11403		0.51	15	*	<0.01	11459	0.03
Pineapples	1200	^	0.02	823	^	<0.01	23	*	<0.01	103		<0.01	236	**	0.01	-		-	2385	<0.01
All other fruit	246	^	<0.01	1	*	<0.01	-		-	13	*	<0.01	257	*	0.01	26	*	<0.01	543	<0.01
Total area (ex. grapes)	20724		0.37	1428		<0.01	65	^	<0.01	2272		0.02	16529		0.74	98		<0.01	41115	0.10

[#] Relative Standard Error (RSE); ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%; ** estimate has a RSE greater than 50%. There are no calculated RSEs for row totals.

Table 7 Vegetables grown in Natural Resource Management regions of the Great Barrier Reef catchment, as defined by the Australian Bureau of Statistics 2019-2020 (ABS 2021a).

Commodity	**Burnett Mary**			**Fitzroy**			**Mackay Whitsunday**			**Burdekin**			**Wet Tropics**			**Cape York**			**Total**	
	ha	RSE#	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	RSE	%	ha	%
Beans	411		<0.01	-		-	-		-	2637	^	0.02	-		-	-		-	3048	<0.01
Broccoli	26		<0.01	-		-	-		-	-		-	3	**	<0.01	-		-	29	<0.01
Cabbages	51		<0.01	-		-	-		-	-		-	11	**	<0.01	-		-	62	<0.01
Capsicums	500		<0.01	-		-	-		-	924		<0.01	11	**	<0.01	-		-	1435	<0.01
Carrots	-		-	-		-	-		-	-		-	1	**	<0.01	-		-	1	<0.01
Cauliflowers	3	**	<0.01	<1	**	<0.01	-		-	-		-	-		-	-		-	3	<0.01
Lettuces	11	**	<0.01	-		-	-		-	-		-	-		-	-		-	11	<0.01
Melons	559	*	0.01	2	*	<0.01	20		<0.01	1395		<0.01	179	**	<0.01	15		<0.01	2171	<0.01
Mushrooms	1	**	<0.01	<1	**	<0.01	-		-	-		-	-		-	-		-	1	<0.01
Onions	3	**	<0.01	-		-	-		-	-		-	16	**	<0.01	-		-	19	<0.01
Potatoes	952	**	0.02	-		-	-		-	352	*	<0.01	408	**	0.02	-		-	1712	<0.01
Pumpkins	317	^	<0.01	6	**	<0.01	9		<0.01	570	^	<0.01	288	**	<0.01	5		<0.01	1195	<0.01
Sweet corn	184		<0.01	-		-	-		-	2814		0.02	3	**	<0.01	-		-	3001	<0.01
Tomatoes	494	^	<0.01	-		-	-		-	938	^	<0.01	-		-	-		-	1432	<0.01
All other vegetables	3154		0.06	115	**	<0.01	60		<0.01	653		<0.01	42	*	<0.01	1		<0.01	4024	<0.01
Total	6665	^	0.12	123	**	<0.01	89		<0.01	10283		0.07	962	*	0.04	21		<0.01	18142	0.04

#Relative Standard Error (RSE); ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%; ** estimate has a RSE greater than 50%. There are no calculated RSEs for row totals.

Searching the literature – method

The literature search comprised:

a) A Scopus® search, representing a subscription-based abstract and citation database under copyright by Elsevier (www.scopus.com) and available to Queensland Government Departments (Department of Environment and Science, Department of Resources, Department of Regional Development, Manufacturing and Water, Department of Agriculture). Within the database, search was undertaken representing – search within “article title, abstract, keywords” for terms listed as:

> **[commodity type]** “wheat”, “sorghum”, “cotton”, “pulses”, “avocados”, “mangos”, chickpea OR "faba bean" OR "field pea" OR lentil OR lupin OR "mung bean" OR peanut OR "navy bean" “pineapple”, “citrus”, “orchard”, “vegetable”, “beans OR corn OR melon OR potatoes OR tomatoes OR pumpkin OR capsicum”, “bananas”, “macadamia”, “pineapple”
>
> **[region]** “Queensland”, “Great Barrier Reef”, “Cape York”, “Fitzroy”, “Burdekin”, “Burnett Mary”, “Mackay Whitsunday”, “Wet Tropics”
>
> **[GBR science category]** “pesticides”, “water quality”, “nitrogen”, “phosphorus”, “runoff”, “sediment”, “insecticides”, “herbicides”, “fungicides”, “nutrients”, “Water management”, “Water Use Efficiency”, “Irrigation”

Through consultation with DES library services, a combined search term was created for cross-checking purposes, listed as:

> (TITLE-ABS-KEY (pesticide* OR insecticide* OR herbicide* OR fungicide* OR "water quality" OR nitrogen OR phosphorus OR runoff OR run-off OR sediment OR “run off” OR erosion OR nutrient* OR “water management” OR “water use efficiency” OR irrigation) AND TITLE-ABS-KEY (Reef OR Queensland OR “cape york” OR fitzroy OR burdekin OR “burnett mary” OR “mackay whitsunday” OR “wet tropics”) AND TITLE-ABS-KEY (commodity type))

b) Internet search-engine and other reference library searches by commodity type and categories as applied above, presented through QG agency, industry-specific, regional-body and other non-government websites. Categories reported in this search include:

> **[commodity classes]** “cereals”, “sorghum”, “wheat”, “pulses”, “hay”, “silage”, “irrigated cotton”, “bananas”, “tree crops”, “macadamias”, “avocados”, “vegetables”, “pineapples”
>
> **[website]** e.g. Government Agency; Industry-specific
>
> **[search date]**
>
> **[access option]** e.g. as open or restricted access to information
>
> **[type]** e.g. PDF report, guideline
>
> **[DOI]** whether the reference has a digital object identifier
>
> **[summary notes]**

Results obtained from a) and b) were captured in a metadata file (excel spreadsheet), with relevant information then transferred and managed through Mendeley reference manager (www.mendeley.com).

Reporting against literature search criteria

Information obtained from the literature search was collated for in-scope commodity types addressed under ALUM 3.0 and ALUM 4.0 classes, according to search questions (italics) within each category (bold) outlined as:

Snapshot of Industry

- *Summary of industry e.g. management, climate, extent*
- *Does the commodity representative industry(ies) refer to best management practices? If so, what context and format?*
- *to what extent are the major focus categories (water, sediment, nutrients, pesticide) considered in the(se) key strategic documents for the commodity type?*

Water

- *Is the commodity type predominantly rain-fed, or water managed through irrigation application?*
- *If irrigated, how much is applied and how is it applied (dominant water source or used intermittently/seasonally)?*
- *How is the commodity considered/managed in relation to water use efficiency?*
- *Note: need to consider water in relation to water quality parameters as applied in reef consensus statement, including interaction of water and nutrients in relation to off-site movement (e.g. groundwater, surface-water runoff) and nutrient transformation processes (and potential losses) occurring as a result of water management*

Sediments

- *What are key considerations for this commodity type in relation to erosion and runoff, for example a) runoff quantity, could cross-reference water use efficiency, discussed above; b) runoff quality. Can refer to what is measured and what they might relate to e.g. nutrients.*
- *Is there information specifically relating to fine sediment?*

Nutrients

- *Application (rate, how, where)*
- *Nutrient use efficiency and loss pathways.*
- *Is there information specifically relating to (i) particulate P (PP) (ii) particulate N (PN) and (iii) dissolved inorganic N (DIN)?*

Pesticides

- *Type and amount (potentially summarised by key peak body reviews)*
- *Pesticide use efficiency and loss pathways (linked to water and sediment)*

Production from dryland agriculture and plantations

Dryland agriculture (excluding sugarcane) in the GBR catchments accounts for 1.79% or 765,793 ha of the land area. The region with the largest percentage of land area under dryland agriculture is the Fitzroy (3.56%), followed by Burnett Mary (1.20%) and Burdekin (0.94%). Cropping accounts for >99% of the area attributed to dryland agriculture. The cropping class in QLUMP includes cereals, beverage and spice crops, hay and silage, oilseeds, cotton (non-irrigated), alkaloid poppies and pulses. However only a small proportion of the area classified as cropping is further classified to these tertiary classes in QLUMP, limiting more detailed assessment. ABS data, which has finer level categorisation includes barley, maize, oats, rice, sorghum, wheat, cotton, canola, chickpea, other oilseeds and other pulses (sugarcane area is excluded for our purposes) in the cereal and other crops class. Wheat, chickpea and sorghum make up 79% of the area of cereal and other crops (excluding sugarcane) across the whole GBR catchment and therefore they are considered further in this section. Hay and silage is separated into its' own class at the same level as cereals and other crops and accounts for 0.12% of the GBR catchment.

Dryland agriculture production is reliant on both in-crop rainfall and rainfall stored as soil moisture during fallow periods. The highest area weighted rainfall average was in the Wet Tropics which received 1,980 mm/yr during the 30 years from 1989–18 (Bureau of Meteorology, 2019a). The lowest rainfall was in the Fitzroy with 670 mm/yr (Bureau of Meteorology, 2019b), while the Burdekin received 680 mm/yr (Bureau of Meteorology, 2019c), Burnett Mary 830 mm/yr (Bureau of Meteorology, 2019d), Cape York 1,450 mm/yr (Bureau of Meteorology, 2019e) and Mackay Whitsunday 1,540 mm/yr (Bureau of Meteorology, 2019f). It should be noted that the three regions (i.e. Fitzroy, Burnett Mary and Burdekin), with the largest percentage of area cropped to dryland agriculture also have the three lowest area weighted rainfall averages of all GBR catchment regions. This is because they extend further inland and are located at higher latitudes.

The year-to-year variability and seasonal variability in rainfall not only impacts the productivity of dryland agriculture but also impacts the movement of runoff, sediments, nutrients and pesticides. Rainfall is highly seasonal throughout the GBR catchments, with the main rainfalls over summer. A summary of the year-to-year variability of rainfall in each region has been formulated by the Bureau of Meteorology in their Regional Weather and Climate Guides. Briefly for the three dominant dryland agriculture regions: The Burdekin has unreliable (~>60% variability year on year) rainfall from October-December in the build up to the monsoon season, while in the south of the region there is usually reliable (~40% variability year on year) rainfall from January-April during monsoon season, and unreliable rainfall (~50% variability year on year) in the north, near Ayr, Townsville and Charters Towers (Bureau of Meteorology, 2019c). In the Burnett Mary during the wet season from October to April, rainfall is reliable (~10–40% variability year on year), while during the dry season from May to September in the south rainfall is moderately reliable (~40% variability year on year) and unreliable in the north (~50% variability year on year) (Bureau of Meteorology, 2019d). In the Fitzroy, Winter and Autumn rainfall is unreliable (~>60% variability year on year), while Summer rainfall is usually reliable in the South and West (~40% variability year on year) and unreliable in the north east (~>60% variability year on year) (Bureau of Meteorology, 2019b). This rainfall variability translates into highly variable year to year water quality impacts from dryland agriculture.

The interaction of rainfall with management practices (e.g. tillage, controlled traffic, stubble management, application timings), soil properties (e.g. particle size, sodicity) and topography (e.g. slope) have the potential to exacerbate or mitigate runoff and associated losses from dryland agriculture.

Cereals and pulses (wheat, sorghum, pulses)

Cereals and pulses are frequently grown in rotation to produce benefits for the whole farm system. Benefits can include providing fixed N to a subsequent crop, disease control, weed control, maintaining soil structure and providing a diversified income from pulse grains. Because the two crop types are intrinsically linked in the farm system, they are considered jointly in this report.

The three NRM regions with the largest areas cropped to cereals and pulses according to the ABS in 2019–20 was the Fitzroy (253,367 ha), Burdekin (100,746 ha) and Burnett Mary (25,460 ha). Pulses as defined by the ABS are chickpeas, faba beans, field peas for grain, lentils, lupins, mung beans, navy beans and peanuts. Cereals as defined by the ABS include barley, maize, oats, rice, sorghum, and wheat. Across the entire GBR catchment the percentage area of cereals and pulses combined, cropped to wheat, sorghum and pulses was evenly split in 2019–20 at 34, 23 and 25% respectively. Wheat was estimated to be grown by 182, 51 and 40 growers in the Fitzroy, Burnett Mary and Burdekin, respectively, while sorghum was grown by 172, 87 and 33 growers in the Fitzroy, Burnett Mary and Burdekin, respectively (Table 8). Chickpeas accounted for 95% of the pulses planted in the GBR catchment in 2019–20 (Table 5). It was estimated in 2019–20 that there were 117 chickpea growers in the Fitzroy and 39 in the Burdekin (Table 8). The two main pulses planted in central Queensland (Fitzroy NRM) in 2016 were chickpea and mungbean, with central Queensland having the largest proportion of cropped area planted to pulses in Australia (GRDC, 2017).

In the GBR catchment wheat and chickpea are winter crops, while sorghum and mung bean are summer crops. This provides farmers with the option to plant either a pulse or cereal in either winter or summer when conditions are favourable. Crops can be planted back-to-back with only a short (one month) fallow between harvest and planting of the next crop, or long (12 months) fallow if conditions such as soil moisture and rainfall, are not conducive to planting. Fallows are primarily used to store soil moisture for the sowing of a subsequent crop. The average percentage of cereal crop area planted after a long fallow in central Queensland was 18.0 and 19.8% in 2014 and 2016, respectively (GRDC, 2017). While the percentage of cereal crop area planted following a pulse crop in the previous year was 27.6, 17.8 and 22.3% in 2011, 2014 and 2016 respectively (GRDC, 2017). This data indicates that approximately 60% of the area planted to cereal in 2016 likely followed another cereal crop, other crop or short fallow.

Cereals and pulses grown within the GBR catchment fall within the Northern Grains Region and often have differing soil management regimes compared to southern regions. In central Queensland (Fitzroy) there is a high uptake of zero tillage (44.6%; <10% soil disturbance), compared to the national average of 14.8% (GRDC, 2017). While no-tillage (10–30% soil disturbance) is practiced on a further 38% of land sown to cereals and pulses (GRDC, 2017). A high adoption rate of 60.5% for controlled traffic compared to the national average of 29.3% is due to the extensive clay soils used for cereals and pulses (GRDC, 2017). Stubble retention where stubble is left intact and standing up to planting accounted for 57.9% of the area planted, while a further 11.1% had stubble retained but not standing and 21.3% had stubble incorporated via tillage (GRDC, 2017). No stubble burning was recorded as it is generally not practiced in Queensland.

The Grains Best Management Practices Program (GrainsBMP) is the industry lead BMP program that started in 2008 with the aim of increasing farm profits and environmental outcomes in the grains industry. The BMP consists of 5 key modules: pesticide application; property design and layout; making best use of rainfall; integrated pest management; and crop nutrition and fertility management (Eames and Collins, 2017). The modules are delivered through workshops and self-assessment. Some of the measured practice change which form the Grains Management Practice Framework are adoption of minimum or zero tillage, constructing contour banks, determination of N requirements, N application timing, influence of stored soil moisture on yield and N rates, adoption of technology that improves pesticide efficacy, controlled traffic adoption and GPS guidance systems (Eames and Collins, 2017; Star et al. 2016). The program is likely responsible for some of the previously mentioned increased adoption rates of management practices (e.g. controlled traffic, zero tillage) in the Fitzroy. In 2013 in the Fitzroy, the majority of grain growers in the GBR catchment were classed in the C category for runoff and soil loss (58%), B category for herbicide management (65%) and B category for nutrient management (53%). However, in a prioritisation report assessing catchments in the Fitzroy Star et al. (2015) stated that there was “relatively low levels of reef investment in the cropping industry in pursuit of sediment, nutrient and herbicide reduction outcomes”. In 2018 an assessment of the uncertainty in the grains industry management benchmarks formed for the Reef 2050 WQIP stated there was moderate confidence in the benchmarks and uncertainty arose due to no fit for purpose datasets for some practices and sometimes divergent views on some practices (Queensland Government, 2018). These summations indicate that more experimental work and investment is required to clarify grain’s management impacts on water quality.

Water

Cereal and pulse rotation systems in the GBR catchment are heavily reliant on rainfall and associated soil moisture, and therefore are generally opportunistic. Crops may or may not be sown depending on soil moisture availability. This variability in planting can leave the soil exposed to rainfall over the high rainfall summer season when runoff losses are more likely to occur. Runoff can be exacerbated when there is no crop planted over summer, there is low stubble retention from the previous crop, or if a summer crop has not closed its canopy to intercept rainfall.

Interestingly, runoff studies in cereals and pulses in the GBR catchment have occurred at individual sites over longer timeframes than most other commodities. From 1983 to 1993 runoff was recorded from a Vertosol near Capella in the Fitzroy NRM, which was cropped with wheat, sorghum and sunflowers (Carroll et al. 1997). Over the ten-year period 54 rain events produced runoff. Annual mean runoff from 1984 to 1990 was reduced by 28% when the previous crop was wheat (19.1 mm/yr) compared to sorghum (26.7 mm/yr). This was due to higher stubble loads after wheat and drier soil profiles after wheat causing large cracks in the Vertosol soil which allowed higher infiltration. Wheat stubble provided 90% cover after harvest while sorghum stubble only provided 58% cover (Sallaway et al. 1988). Zero tillage (19.1 mm/yr) reduced annual mean runoff by 43% compared to conventional tillage (33.3 mm/yr), as stubble coverage was maintained for longer periods.

Another study on a Vertosol cropped predominately to wheat, sorghum and chickpeas in the same region as the previous study measured run off between 1999 and 2018 (Murphy et al. 2013; Rogusz et al. 2013; Rogusz and Burger 2017; Rogusz, 2019). Annual mean runoff from 1999 to 2018 was 77 mm/yr, which was 14% of the long-term annual rainfall (Rogusz, 2019). However, variability between years can be high, with multiple years recording no runoff (e.g. 2002, 2004, 2006) in contrast to 343 mm of runoff recorded in 2007 which was 41% of rainfall (829 mm) (Murphy et al. 2013).

Runoff was also measured from a Ferrosol cropped with maize (two years) and peanut (one year) in the Wet Tropics NRM over three years. The data was used to calibrate the PERFECT model to predict long-term runoff under different management practices. Modelled long-term (1905–-2001) average annual runoff decreased in the order: conventionally tilled (CT) peanuts (82 mm/yr) > reduced till (RT) peanuts (73 mm/yr) > CT maize (71 mm/yr) > RT Maize (53 mm/yr) (Cogle et al. 2011). Practices that created the lowest surface cover were generally found to have higher runoff. Modelled long-term average drainage were generally similar between the four crop treatments ranging from 621 to 648 mm (Cogle et al. 2011).

Another study on a Vertosol soil in the Fitzroy NRM examined runoff from wheat and sorghum in rotation with cotton over four years. Runoff generally decreased as ground cover and soil water deficit increased (Hulugalle et al. 2002). Rotations with a longer fallow had higher soil moisture, lower soil cover and increased runoff. These results show the importance of a whole of system approach to minimising runoff, as each crop can affect the ability of the system to combat runoff losses, both during crop growth and during subsequent crops.

A study on a Vertosol near Emerald in the Fitzroy NRM assessed runoff from differing rotations of sorghum, wheat and cotton over 3 years (Hulugalle et al. 2002). Conclusions drawn were that crops sown early and grown over summer were able to reduce runoff by intercepting rainfall, and that increased groundcover reduced runoff. The level of groundcover during crop growth increased in order: wheat (47% cover) < cotton (52% cover) < sorghum (68% cover). Fallow only had 9% ground cover.

The longest relevant cropping study originates from the Brigalow Research Station, where cropping on a Sodosol soil was initiated in 1984 after clearing in 1982 (Cowie et al. 2007). The trial is currently opportunity cropped to wheat and sorghum with minimum till practiced after 1992. Prior to 1992 conventional tillage was practiced. From 1985 to 2004 runoff from cropping increased to 11% of rainfall compared to 5% for native vegetation (Thornton et al. 2007). From 1983 to 2000 under cropping deep drainage averaged 19.8 mm/yr, ranging from 3.3 to 50 mm/yr, which was lower than the average drainage recorded when the land was left bare between 1981–83 (59 mm/yr) (Silburn et al. 2009). Comparisons between old and new farming systems was difficult due to sampling times, however Silburn et al. (2009) reports that it is expected that less tillage and more summer and opportunity cropping in new systems will have about half the deep drainage of old farming systems characterised by more tillage, less stubble retention and a wheat/fallow rotation. Increased drainage often associated with zero/minimum tillage compared to conventional tillage is counteracted by sowing summer crops in new farming systems. The risk posed by deep drainage salinity to groundwater has not been fully assessed, however the leachate was found to be saline with the potential to salinise groundwater (Silburn et al. 2009).

Sediment

Research on sediment losses from cropping in the Great Barrier Reef catchments has primarily focussed on the heavily cropped Fitzroy catchment. Sediment tracing has indicated basaltic clays, which are made up of very fine particles, are a major source of sediment discharged from the Fitzroy catchment (Lewis et al. 2015). Cropping in the Fitzroy predominately occurs on these basaltic clays and therefore management practices that can reduce these sediment losses have been investigated and trialled.

Contour banks, when correctly designed and maintained, provide erosion control on cropping lands. Over nine years, from 2000 to 2008, a single spaced (180 m) contour bay lost 11 t/ha soil in runoff, while a triple spaced (450 m) contour bay produced 16 t/ha (Murphy et al. 2013). This was due to increased sediment concentrations in runoff, not due to increased runoff. High variability in annual soil losses was evident with losses ranging from nil to 3.5 t/ha and nil to 4.9 t/ha soil loss for single and triple spaced contour bays, respectively (Murphy et al. 2013). The variability was mainly driven by soil cover and rainfall. At the same site, after the previous study, from 2009–18 (excluding data from 2012–13) approximately 16.8 t/ha soil was lost in runoff from the single-spaced contour bay, ranging from 0.26 to7.4 t/ha annually (Rogusz et al. 2013; Rogusz and Burger 2017; Rogusz 2019). The largest annual soil loss coincided with low ground cover of 18% caused by a dry season which decreased yields and biomass (Rogusz 2019). A total of approximately 28 t/ha was lost in runoff from the single-spaced contour bay over 18 years.

Total suspended solids were measured in runoff from the Brigalow Catchment study from 2000–10. The cropped area gave an average EMC of 798 mg/L, which is 2.6 and 3.5 times larger than a comparable woodland and pasture area, respectively (Elledge and Thornton 2017). Coupling the EMC data and runoff data from a 25-year period from 1984–2010, modelled TSS loads over 25 years was 525 kg/ha/yr, which was 6.5 and 4.4 times the loads from woodland and pasture areas, respectively (Elledge and Thornton 2017). Erosion rates from Brigalow cropping was also estimated using the Caesium-137 technique. This method estimated soil loss of 14.7 t/ha/yr, which is significantly higher than the amount modelled over 25 years and was the highest recorded from the 13 sites tested in the study which included other cereal sites, grazing, pasture and vegetable sites (Loughran and Elliott 1996). Two other cereal cropped sites also in the Fitzroy recorded erosion rates of 5.5 and 1.3 t/ha/yr using the Caesium-137 technique (Loughran and Elliott 1996).

Over six years soil loss in runoff was measured from a wheat, sorghum and sunflower rotation near Capella. The average soil loss from zero tillage was 1.42t/ha, which was 65% lower than that from conventional tillage (Carroll et al. 1997). Soil loss when wheat stubble was present was 1.34 t/ha which was 55 and 56% lower than when stubble from sorghum or sunflower was present (Carroll et al. 1997). Soil cover of >30% was found to be required for erosion control, which is why zero till and wheat stubble reduced erosion losses compared to conventional till and stubble from sorghum or sunflower, respectively (Carroll et al. 1997).

Over three years on a Red Ferrosol in the Wet Tropics, annual total soil loss from a maize and peanut rotation ranged from 0.3 to 6.2 t/ha/yr, with no significant difference between conventional or reduced tillage (Cogle et al. 2011). In comparison bare ground over the same period lost between 10.4 and 30.6 t/ha/yr, showing the benefit and importance of having soil cover during the summer rainfall season. The large variability seen over the measured three years was negated when annual erosion losses were modelled over the long-term (1905–2001). The largest modelled soil loss was 2.6 t/ha/yr from CT peanuts and the lowest was 0.5 t/ha/yr from RT maize.

In a cotton, sorghum and wheat rotation suspended sediment loads were 2–4 times greater than the bed load (Yule and Rohde 1996). Suspended sediments pose a greater risk of being transported further in waterways compared to bed load (Yule and Rohde 1996). Total suspended loads decreased with increasing stubble cover, with at least 50% soil cover recommended to control erosion (Hulugalle et al. 2002; Rhode and Yule 1995), which is higher than the 30% threshold suggested by Carroll et al. (1997).

Nutrients

Historically soils on which cereals have been grown did not require additional inorganic fertiliser applications, as the soil was inherently fertile and able to supply the crops' nutrient requirements. However, after 40–50 years of cropping supplementary nutrients are required to maintain yields on brigalow lands used for cropping in central Queensland due to the rundown of soil fertility (Cox and Strong 2017). Indeed, negative N, P and K budgets for central Queensland grain growing indicates mining of soil reserves, which is not sustainable in the long-term (Bell et al. 2010).

Across Australia, it is predicted that to maintain dryland cropping, assuming no increase in nitrogen use efficiency (NUE), fertiliser application will have to double from 45 kg N/ha in the next five decades (Angus and Grace, 2017). Thorburn and Wilkinson (2013) assumed 100 kg N/ha/yr was supplied to grain crops in the GBR catchments from fertiliser, soil mineralisation and legume fixation combined, with only 10% of that N assumed to be surplus to the system, which is very small in comparison to other crops (e.g. bananas and sugarcane). Within the GBR catchment it was estimated in 2013, 31–40 kg N/ha was applied as fertiliser to cereals in the Fitzroy with 40.3–52 kg N/ha exported offsite in grain, equating to a deficit of approximately 10 kg N/ha (Star et al. 2015). Even though there may be an overall N deficit and only a small N surplus in the system, fertiliser N can still potentially contribute to increased DIN concentrations in runoff when not managed effectively. From 74 isotope fertiliser studies across different cereals in Australia an average of 44 ± 14% of the applied N was recovered in the aboveground biomass, 34 ± 14% in the soil and 22 ± 16% was not recovered (Angus and Grace 2017). Nitrogen which is unrecovered (22 ± 16%) is potentially lost offsite via leaching, runoff, denitrification and ammonia volatilisation.

Yield response to applications of P have also been observed at some locations in the Northern Grains Region, indicating that P may also be depleted in some instances (Bell et al. 2012). Therefore, application of fertilisers to cereals has been recommended and methods for calculating required inputs have been suggested. One such method includes calculating N demand of the crop taking into account a grain protein target, yield target and fraction of N in protein (different for sorghum and wheat), then subtracting the N supplied by soil (Cox and Strong 2017). A more sophisticated approach is freely available online via the Agricultural Risk Management Tools published by the Queensland Government and University of Southern Queensland. One tool in this suite is NitrogenARM, which calculates the N application rate required for either wheat or sorghum, taking into account soil mineral N supply, potential seasonal yields and simulated crop growth (State of Queensland and University of Southern Queensland, 2017). Sites that are selectable in the program include a number which are within the GBR catchment including Mareeba, Walkamin, Atherton, Kairi, Clermont, Emerald, Banana, Dululu and Bundaberg.

The amount of N contained in soil at planting and mineralised from soil during crop growth is vital in determining the supplementary N required in the form of fertiliser. A GRDC survey from 2016 indicated that soil testing informed fertiliser programs on 54.9% of the area sown to cereals in central Queensland, which is below the national average of 65%, improved from 2014 (GRDC 2017). Similarly, 52.1% of the cereal area used fertiliser rates determined by crop removal, which was below the national average of 67.4% (GRDC 2017). There is a consistent message, which is generally in contrast to other commodities, that fertiliser application rates to cereals may in many instances need to be increased to make the system sustainable. However, this could lead to higher offsite movement of nutrient loads and could therefore conflict with water quality outcomes.

In contrast to cereals, pulses generally require nil to small amounts of N fertiliser. One of the benefits of planting a pulse crop is that it can acquire its own source of N through N fixation and this N is released into the soil as the plant residues breakdown after harvest. Mineralisation of plant residues release ammonium into the soil which can be converted to nitrate via nitrification. Chickpeas can derive >70% of their N requirement from nitrogen fixation (GRDC 2016). However, high soil nitrate concentrations, either from fertilisation or soil mineralisation, greatly inhibit N fixation which negates one of the benefits of a pulse crop. Nitrogen rates of 5–15 kg N/ha applied at planting does not negatively impact chickpea N fixation and may help the crop establish a strong root system (Pulse Australia 2021). Nitrogen provided to the system from a pulse crop is largest when harvest index is low, that is when grain yield is low and biomass is high (Cox and Strong 2017). The amount of N provided by chickpea and mungbean crops grown near Biloela averaged 35 kg N/ha (16–51 kg N/ha) and 34 kg N/ha (25–42 kg N/ha), respectively over three years (Cox et al. 1998; Cox and Strong 2017). The release dynamics of the biomass N from pulses is governed by the prevailing climatic and soil conditions (e.g. temperature, soil water content) and the properties of the biomass itself especially the C:N ratio. The C:N ratio of pulses is generally smaller than that of cereal stubble, subsequently the mineralisation and release of N can be faster than cereals. This has implications for the stubble coverage provided by pulses, since as they breakdown faster the soil will be exposed to rain events for longer periods therefore affecting overall runoff and associated losses of sediments, nutrients and pesticides. Pulse crops are also noted as generally having low stubble coverage initially after harvest, which also can leave the soil exposed (Cox and Strong 2017).

There are more measurements of nutrient losses from cereals than pulses in the GBR catchments. Studies have not exclusively measured nutrient losses from pulses, although they have been measured when in rotation with cereals. Modelled nutrient losses from an unfertilised cropping (wheat, sorghum and chickpea in rotation) catchment over 25 years was total nitrogen (TN) of 3.53 kg/ha/yr, organic nitrogen (ON) of 1.43 kg/ha/yr, DIN of 1.5 kg/ha/yr, ammonium (NH_4-N) of 0.07 kg/ha/yr, total phosphorus (TP) of 0.61 kg/ha/yr and dissolved inorganic phosphorus (DIP) of 0.23 kg/ha/yr (Elledge and Thornton 2017). This estimation was based on 10 years of measured nutrient and runoff data, and 25 years of runoff data. The mean EMCs for the measured 10 years was TN of 5.37 mg/L, organic nitrogen of 2.17 mg/L, NH_4-N of 0.11 mg/L, DIN of 2.27 mg/L, TP of 0.93 mg/L and DIP of 0.35 mg/L. As this cropping system does not receive supplementary nutrients it is not representative of current practices, but it does give an indication of the N and P which may be lost from background soil mineralisation in a rundown cropped soil.

Nutrient losses were measured over two years in a fertilised Kandasol sown to maize and peanuts on the Atherton Tablelands. 80 kg N/ha and 25–30 kg P/ha were applied to maize while 40 kg P/ha were applied to peanuts (Cogle et al. 2011). Over the two years annual N losses from cropped soil (under RT and CT) ranged from 3.6 to 17.4 kg/ha and P losses ranged from 3.3 to 11.5 kg/ha.

Losses of nutrients were measured over one season from a sorghum site fertilised with 37 kg N/ha in the Fitzroy (Murphy et al. 2013). Average concentrations in runoff of TN were 7.3 mg/L, which were dominated by NO_x-N (5.9 mg/L), followed by PN (1.4 mg/L), DON (1.1 mg/L) and ammonia (0.2 mg/L). The high proportion of NO_x-N was due to fertiliser inputs and it was estimated that approximately 20% of the applied N was lost in runoff as NO_x-N when contour bays were double spaced (Murphy et al. 2013). Average concentrations in runoff of TP were 0.53 mg/L which were dominated by PP (0.41 mg/L), DOP (0.016 mg/L) and FRP (0.017 mg/L). In the next season winter wheat was sown with 41 kg N/ha and 4.2 kg P/ha, followed by chickpea with no supplementary fertilisers. Over this period the seasonal average concentration of TN declined from 8.7 mg/L to 3.5 mg/L, driven by lower rainfall post wheat fertilisation and no fertiliser application to chickpeas, although NO_x-N still made up 71–75% of the TN (Rogusz et al. 2013). In contrast, DIN only made up 10–14% of TN in a runoff event that occurred after an extended period of no fertiliser application due to a fallow and/or chickpea crop (Rogusz and Burger 2017; Rogusz 2019), however DIN contributed 70% of TN in runoff shortly after fertilisation with ~84 kg N/ha (Rogusz and Burger 2017). This highlights that the proportion of DIN in runoff increases after N fertilisation. In the same study it was noted that ensuring fertiliser is placed in the soil and covered over is vital in reducing N loads in runoff, with previously mentioned high applied N losses (i.e. 20%) likely caused by fertiliser not being placed deep enough in soil and some remaining on the surface. In subsequent seasons, after implementation of new machinery to ensure fertiliser was buried, N lost in runoff decreased from 7–8 kg/ha to ~0.5 kg/ha (Rogusz, 2019).

Cereal and pulse cropping, as already highlighted, occurs predominately on the basaltic clays in the Fitzroy which are made up of very fine particles. These fine particles are not only able to travel further in runoff and water ways, but there are increasing concerns regarding the bioavailable N that can be released from the associated organic N components (Lewis et al. 2020). The PON and DON can be mineralised offsite to form DIN, while the PIN (particulate inorganic nitrogen) can be converted to DIN via ammonium desorption (Lewis et al. 2020). So, although there has been a focus on DIN concentrations in runoff, the organic N component is also important and may be more important in systems such as cereals and pulses that do not have comparatively large additions of inorganic N fertilisers. Seasonal average TN concentrations in runoff reported from cereal and pulse studies can be larger than those reported from some sugarcane studies with more N applied (Rogusz et al. 2013), which has been theorised to occur due to the inherent fertility of the basaltic clays cropped to cereals and pulses (Waterhouse et al. 2015). Quantification of the soils ability to supply N to cereals and pulses would help to clarify the source of N being lost in runoff.

In the case of pulses, which serve to benefit the crop rotation by adding N to the system from mineralisation of organic N in residues, the availability of that N over time and its susceptibility to being lost in runoff has not been addressed within the context of water quality impacts. Although the N is fixed from the atmosphere it eventually becomes part of the soil system and is prone to the same loss processes as N applied by farmers. Long-term experiments already measuring water quality in runoff at sites cropped to pulses provide an opportunity to better understand the dynamics of N loss from pulses if soil transformations of fixed N from residues is also studied in tandem in those experiments.

Pesticides

A dichotomy exists between the use of zero till to decrease runoff and soil loss from cropping lands, and the need for pesticides to be used to control weeds under zero till (Star et al. 2016). Traditionally, conventional tillage would control weeds during a fallow phase, however with the adoption of zero till pesticides are used, which increases the potential for pesticide losses. So, although runoff, which moves pesticides offsite, may decrease with zero till, there is a risk that farmers may increase pesticide usage to control weeds which will potentially increase the amount lost offsite. Indeed in 2016, 53.5% of the area under fallow in central Queensland was only managed with herbicides (GRDC 2017). The use of herbicides can be reduced by increasing the efficiency of herbicide applications and targeting weeds specifically, which has been a focus of GrainsBMP (Eames and Collins 2017).

Measurement of pesticide losses from cereal crops has primarily occurred in the Fitzroy NRM. The most temporally comprehensive monitoring of pesticide losses from a cereal crop occurred in the Gordonstone catchment in the Fitzroy. In 2009–10 Metolachlor was detected in runoff up to 38 days after application. Approximately 9.6% (139 g a.i./ha) of the applied Metolachlor was lost in 4 runoff events (Murphy et al. 2013). In contrast, in the 2015–16, 2016–17 and 2017–18 seasons from the same site 0.3, 1 and 3%, respectively, of the applied Metolachlor was lost annually in runoff (Rogusz 2019). This was partly attributed to a reduction in the rate of Metolachlor applied. Other pesticides which were detected to varying degrees in runoff water from this trial included atrazine, simazine, isoxaflutole, 2,4-D and fluroxpyr (Rogusz et al. 2013; Rogusz and Burger 2017; Rogusz 2019). Notably Atrazine and Simazine were detected in runoff for up to three and one years, respectively, after application (Rogusz et al. 2013). In contrast, glyphosate was found to not have residual build up in soil after 7–8 years of applications, which is expected for non-residual chemicals (Hargreaves and Noble 1993). Half-lives of two and seven days were determined for glyphosate and 2,4,D, respectively, on soil/stubble in the Fitzroy region NRM under reduced tillage (Hargreaves and Noble 1993). Half-lives of Atrazine and Metolachlor after application to soil were calculated at 17 and 14 days, respectively (Rogusz and Burger 2017). In another study in the same region up to 14% of the applied atrazine was lost in one runoff event, with a maximum concentration of atrazine in runoff of 660 ug/L recorded (Carroll 2004). In a separate study in the Gordonstone catchment runoff from two cropping sites were sampled to assess the partitioning of pesticides between the dissolved and particulate phase. No partitioning (i.e., all pesticides in the dissolved phase) of metolachlor, atrazine and simazine was observed at one site, while at the second site three out of six samples exhibited partitioning (Packett 2014). These results indicate that pesticides used in cropping are likely to easily be transported offsite and downstream as they are predominately in the dissolved phase.

Although the above studies clearly show evidence of pesticide losses from cereal cropping, a modelling study across all cereal growing areas in Australia found that average pesticide concentrations moving offsite would be below trigger values for water guidelines and would only exceed the triggers 1–2 times annually (Freebairn 2014).

Table 8: Estimated number of businesses growing cereals and other crops (excluding sugarcane) by Natural Resource Management regions in the Great Barrier Reef catchment (ABS 2021a).

Commodity	**Burnett Mary**		**Fitzroy**		**Mackay Whitsunday**		**Burdekin**		**Wet Tropics**		**Cape York**		**Total**
	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.
Cereal Crops													
Wheat for grain	51	*	182	^	2	**	40	^	3	**	-		278
Sorghum for grain	87	*	172	^	13	**	33	^	5	**	2	**	312
Barley for grain	47	*	14	*	-		4	*	-		-		65
Maize for grain	49	*	38	*	3	*	13	*	4	**	-		106
Oats for grain	36	**	37	*	-		3	**	5	**	-		81
Rice for grain	-		-		-		5	**	-		-		5
All other cereals for grain or seed	10	**	5	**	-		17	*	-		-		32
Other crops													
Cotton	4	*	39	*	-		1		-		-		45
Oilseeds - Canola	-		1		-		-		3	**	-		4
Oilseeds - Other oilseeds	35	*	4	**	19	**	45	^	-		-		104
Pulses and legumes - Chickpeas	10	**	117	^	2	**	39	^	-		-		167
Pulses and legumes - Other pulses	111	*	61	^	4	**	17	*	4	**	-		197
All other crops	123	*	23	**	3	**	-		34	*	-		183

No. Estimate of number of businesses; RSE Relative Standard Error; ^ estimate has a relative standard error of 10% to less than 25%; * estimate has a relative standard error between 25% and 50%; ** estimate has a relative standard error greater than 50%. There are no calculated RSEs for row totals. The sum of businesses may not equal the total number of businesses as a business may grow more than one commodity.

Other

Commodities in the ‘production of dryland agriculture and plantation’ ALUM class not considered in this review include but are not limited to oilseeds, pastures, hay and silage. Other commodities which are predominately irrigated (e.g. vegetables, tree fruits) have not been included in the dryland class.

Production from irrigated agriculture and plantations

In-scope irrigated agriculture in the GBR catchment accounts for 0.54% of the total land area (Table 2). The Wet Tropics has the highest percent area under irrigation (1.36%), followed by the Burnett Mary (1.30%) and the Fitzroy (0.64%) (Table 2). However, the Wet Tropics only has the third largest irrigated area (30,129 ha), and the Fitzroy has the largest area (100,027 ha), followed by the Burnett Mary (72,818 ha). Across the GBR catchment cropping accounts for the majority of irrigated agriculture, however it is only 16% of the total cropping area (dryland + irrigated cropping). This trend is evident at the regional level only in the Fitzroy region, which is the main reason cropping dominates across the whole GBR catchment. In comparison the irrigated area under horticulture and cropping is similar in the Burnett Mary region, and horticulture dominates in the Burdekin, Wet Tropics and Mackay Whitsunday regions. Cereals and hay and silage were predominately dryland, while rice and cotton were only grown with irrigation (Table 9). Fruit trees, nut trees, plantation fruits and vegetables were predominately grown under irrigation (>80%). It should be noted that the total volume of irrigation fluctuates annually based on rainfall received. Similarly, the irrigation rate also fluctuates between years. The highest reported rates of irrigation in 2019–20 were for cotton and rice with 5.29 and 8.13 ML/ha, respectively (Table 10). Vegetables, fruit trees, nut trees, plantation fruits and cereals all had an average irrigation rate of approximately 3 ML/ha across all regions (Table 10). Although there was variability between regions, some of the variability is caused by data uncertainty, especially when only a small area is reported for a commodity in a specific region.

Data on the source of irrigation water for individual commodities in the GBR catchments was not found. Water source data collected by the ABS covers NRM regions, however, it does not differentiate between commodities (Table 11). The aggregated data also includes irrigation water used for sugarcane which is out of the scope of this report. In 2019–20 reported water source data indicated that the largest source of water in the GBR catchment was from irrigation channels or irrigation pipelines, which accounted for 44% of water use. Water sourced from groundwater sources accounted for 26% of water use and water taken from rivers, creeks, lakes, etc. accounted for 20% of irrigated water. Notable regional exceptions to this trend, include in the Mackay Whitsunday where similar volumes of water were sourced from groundwater (31%) and irrigation channels (29%); in the Wet Tropics similar volumes were sourced from irrigation channels (32%) and rivers, creeks & lakes (34%); and in Cape York 69% of water was sourced from groundwater, however this included areas west of the Great Dividing Range which does not drain into the GBR.

Unlike potential pollutant losses from dryland agriculture, which are driven by rainfall, pollutant and water losses from irrigated agriculture are both rainfall and irrigation driven. In irrigated systems there is the potential to both exacerbate or mitigate losses depending on whether irrigation is managed efficiently. This includes the management of decisions and uncertainty based upon weather, soil properties and crop requirements.

Table 9: Percentage (%) of total area cropped that was irrigated in each commodity class in each Great Barrier Reef Natural Resource Management region for 2019-2020 (ABS 2021b).

Commodity	Burnett Mary	Fitzroy	Mackay Whitsunday	Burdekin	Wet Tropics	Cape York	Total GBR catchment
Cereals for grain or seed, excluding rice	8	4	3	2	*	0	4
Cotton	100	100	-	100	-	-	100
Fruit trees, nut trees, plantation or berry fruits	87	56	49	88	85	99	85
Grapevines	100	59	-	-	-	-	69
Nurseries, cut flowers and cultivated turf	74	0	93	0	75	-	61
Other crops n.e.c	21	7	5	4	22	-	7
Pastures (including lucerne) and cereal crops cut for hay and silage	40	0	21	0	5	0	17
Rice	-	-	-	100	-	-	100
Vegetables	73	96	0	89	96	100	83

* Area under irrigation was larger than the total area reported.

Table 10: Irrigation application rates (ML/ha) for selected commodity classes in each Great Barrier Reef Natural Resource Management region for 2019-2020 (ABS 2021b).

Commodity	Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Mean
	ML/ha	RSE	ML/ha	RSE	ML/ha	RSE	ML/ha	RSE	ML/ha	RSE	ML/ha	RSE	ML/ha
Cotton	3.61		7.25		-		5.00		-		-		5.29
Fruit trees, nut trees, plantation or berry fruits	4.43		3.24		0.84	^	3.26		5.56		0.92		3.04
Vegetables	2.70		4.9		-		3.59		1.59	*	2.38		3.03
Cereals for grain or seed, excluding rice	1.97	^	2.7		0.52		7.13	^	2.69		-		3.00
Grapevines	2.92		4.67		-		-		-		-		3.80
Nurseries, cut flowers and cultivated turf	3.33	*	-		2.02		-		4.78	^	-		3.38
Pastures (including lucerne) and cereal crops cut for hay and silage	3.97		-		1.99	*	-		6.55	*	-		4.17
Rice	-		-		-		8.13	^	-		-		8.13

RSE Relative Standard Error; ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%.

Table 11: Sources of water used for agriculture in each Great Barrier Reef Natural Resource Management region. Note this also includes agriculture which is out of scope of this report (e.g. sugarcane and pasture) (ABS 2021b).

Water Source	**Burnett Mary**		**Fitzroy**		**Mackay Whitsunday**		**Burdekin**		**Wet Tropics**		**Cape York**		**Total GBR catchment**
	ML	RSE	ML	RSE	ML	RSE	ML	RSE	ML	RSE	ML	RSE	ML
Groundwater (e.g. bores, springs, wells)	61628	^	28582	^	42009	^	219407		28474	^	489		380589
Recycled/re-used water from off-farm sources (e.g. re-use schemes, mines)	1437		52	**	5137	**	11153	^	22	**	-		17802
Town or reticulated mains supply	56	*	29	**	2	*	32	**	27	**	-		146
Water taken from irrigation channels or irrigation pipelines	145002		80121		39593	*	347560	^	34063	^	-		646338
Water taken from on-farm dams or tanks	44057	^	27438	^	22149	*	31358	^	7260	*	10		132272
Water taken from rivers, creeks, lakes, etc. - Total	59583	^	93078	*	26075	^	83532	^	36478	^	211	**	298956
Water taken from rivers, creeks, lakes, etc. - Where a volumetric/usage charge occurs	51188	^	63777	*	21442	*	70300	^	19201		-		225908
Water taken from rivers, creeks, lakes, etc. - Where there is no volumetric/usage charge	8395	*	29301	*	4632	**	13232	^	17277	^	211	**	73047
Other sources of water (excluding rainfall)	928		-		-		-		-		-		928
Total volume of water from all sources	312691		229300	^	134965	^	693041		106324		710	^	1477031

RSE Relative Standard Error; ^ estimate has a RSE of 10% to less than 25%; * estimate has a RSE between 25% and 50%; ** estimate has a RSE greater than 50%.

Irrigated cotton

Cotton has been grown consistently in Great Barrier Reef catchments for over 100 years, although its' extent has fluctuated over time (Lewis et al. 2021). Currently, the largest cotton growing region is the Fitzroy, however the Burnett Mary was also a top producer of cotton between the 1920s to 1940s. In 2019–20 there were an estimated 39 cotton growers in the Fitzroy, with only another five growers in other GBR regions (Table 8). Within the Fitzroy, there are two main cotton growing regions, the Central Highlands centred around Emerald, and the Dawson and Callide Valleys, spreading from Theodore to Biloela. Also, within the last 20 years there has been interest and investigations into the viability of expanding the cotton industry into north Queensland and in particular the Burdekin, where cotton could be grown in rotation with sugarcane (Grundy et al. 2012; Yeates 2015; Yeates et al. 2013).

Results from the 2020 CRDC grower survey of cotton growing in central Queensland, which is primarily located in the Fitzroy, indicates that cotton growing is dominated by furrow irrigation, conservation of residues and minimum tillage (CRDC 2020a), primarily on heavy clay soils (e.g. Vertosols). Despite the dominance of furrow irrigation in cotton growing, the 2017 Scientific Consensus indicates for cotton "there are few studies on the effect of irrigation management on nutrient losses in Great Barrier Reef catchments" (Eberhard et al. 2017). In addition, a review of Australian based data for water quality modelling in 2012 found insufficient data for cotton (Bartley et al. 2012), and only referenced one dataset originating in the Fitzroy from 1993–96 (Noble et al. 1996).

Over the last 20 years, the wider Australian cotton industry has focussed on improving water use efficiency (WUE) and reducing reliance on pesticides through the cotton industry's voluntary BMP program (myBMP 2021). As of 2019 approximately 66% of the Australian cotton industry was registered for myBMP and 18% were accredited (CRDC 2019). Numerous topic-specific documents have been formulated by industry to form part of myBMP. These include NUTRIPAK, a practical guide of cotton nutrition which includes BMPs for nutrient management; WATERpak, a guide for irrigation management in cotton and grain farming systems which includes BMPs for water use efficiencies; SOILpak, which includes BMPs for managing soil resources in cotton production; SPRAYpak, cotton growers' spray application handbook which has BMPs for the application and use of pesticides in cotton production; NORpak, cotton production and management guidelines for the Burdekin and north Queensland coastal dry tropics region, which provides a region-specific BMP focus; and the Australian cotton production manual which is a key reference manual for BMP in cotton.

Water

Water use efficiency has been in considerable focus across the Australian cotton industry beginning in the early 2000s due to ongoing water scarcity and the heavy reliance of the industry on irrigation. Benchmarking of current practices was undertaken to ascertain several indices of WUE and to investigate where losses were occurring in the farm system and how to decrease them. Briefly some of the indices calculated included gross production water use index (GPWUI): the gross amount of lint produced per unit volume of total water input (including rainfall and irrigation); Irrigation water use index (IWUI): the gross amount of lint produced per unit volume of irrigation water only; and whole farm irrigation efficiency (WFIE): the amount of irrigation water available and used by crops on the farm as a percentage of total irrigation water inputs to the farm (Roth et al. 2013).

Although benchmarking of WUE was undertaken across the industry, there is no explicit data that represents all cotton in GBR catchments. A selection of the data collected which includes some data from cotton grown in GBR catchments are a GPWUI of 1.12–1.20 bales/ML from cotton farms in Queensland (Goyne and McIntyre 2003), a GPWUI of 1.13 bales/ML from Emerald cotton farms (Queensland Department of Primary Industry and Fisheries, 2009), a IWUI of 1.31–1.97 across two years from farms between Hillston and Emerald (Trindall et al. 2012), and WFIE of 58–60% from cotton farms located across Queensland (Goyne and McIntyre 2003). These examples were mainly taken prior to BMP adoption or during adoption phases of BMP and more recent data for GBR catchments is lacking. In the 2020 cotton growers survey an average GPWUI of 1.22 bales/ML was reported from a limited sampling of 14 cotton farms in central Queensland (CRDC 2020a). From 2003–10 there was a 40% increase in overall cotton WUE across the whole industry (as measured by GPWUI), which was attributed to new cultivars and improved land management practices (Roth et al. 2013). Improved land management practices include optimised irrigation scheduling, minimum till, crop trash retention and controlled traffic. The cost to change from furrow surface irrigated to more water efficient lateral move, centre pivot or sub surface drip irrigation is prohibitive and therefore has not been widely adopted (Roth et al. 2013).

Deep drainage and runoff are two loss pathways that decrease WUE and have the potential for adverse offsite impacts in cotton cropping. Deep drainage losses were historically assumed to be low for heavy clay soils, which are dominant in cotton growing regions of the GBR catchment, however this has been disproven (Silburn et al. 2013a). Using data collected from Southern Queensland cotton farms, outside of the GBR catchments, deep drainage losses were calculated at 42.5 mm per irrigation event which equated to 2.5 ML/ha (Smith et al. 2005). Deep drainage was calculated as 16% (118 mm) under farmers conventional furrow irrigated practice in the

Emerald irrigation area (McHugh et al. 2008; Silburn et al. 2013a). Similarly, using data collected and modelled from the Emerald Irrigation Area, 19% (246 mm) of irrigation and rainfall was lost as deep drainage when 7.2 ML/ha/yr (720 mm/yr) was applied (Connolly et al. 1998, 1999). Since deep drainage can be significant under irrigated cotton, it has the potential to impact groundwater resources. Indeed, increased groundwater levels have been observed at Emerald and Theodore.

Runoff losses were also considered in the aforementioned study, with 13% or 177 mm of irrigation and rainfall leaving the field as runoff (Connolly et al. 1998, 1999). Although data on runoff from cotton fields is documented across various regions including some located in GBR catchments, Nachimuthu and Webb (2016) noted that there is a lack of data on actual irrigation offsite runoff losses from cotton farms across Australia because an estimated 75% of field irrigation runoff being recirculated. Therefore, true offsite losses from runoff may be considerably less. Similarly, to the recorded WUE data, the majority of runoff and deep drainage data for GBR catchments has a limited focus on the Emerald Irrigation Area in the Fitzroy catchment, and in many cases was collected prior to the widespread implementation of BMP, so may not be applicable under current optimised BMP.

Sediment

All reports on soil loss in GBR catchments from cotton have originated from the Emerald Irrigation Area in the Fitzroy. This has occurred due to concern over the steeper slopes (2%) in the region, being prone to erosion from irrigation and rainfall events. In furrow irrigated systems the sides of the bed have steep slopes, which are prone to erosion from both irrigation and rainfall events. Carroll et al. 1995 reported that 4–5 t/ha of soil was lost from furrow irrigation and rainfall events over one growing season (September-March), with the majority (3–4 t/ha) caused by rainfall events. In another cotton study in the same region conducted over two seasons, soil loss from furrow irrigation was 6.0 and 12.7 t/ha, with an average sediment concentration in irrigation runoff of 4.2 and 5.2 g/L for each season (McHugh et al. 2008; Smith et al. 2003). A study which sampled four locations around a cotton farm (input channel, furrow, tail drain and downstream weir) found median values for suspended solids of 31–1764 mg/L (Noble et al. 1996). Another study reported sediment concentrations in runoff from conventional cotton of 6–15 g/L during storm events and 2–6 g/L during furrow irrigation events (Waters 2001). In a rainfall simulator study from a bare cotton soil, 3.41 t/ha (19.4 g/L) of soil was lost after a simulated storm of 65 mm of rainfall (Silburn and Glanville 2002). However, soil loss quantities reported for cotton farming in many instances may not directly relate to offsite impacts on waterways, as the recirculation of tail-water from furrow irrigation around a farm is common practice. Therefore, soil loss may indicate the movement of soil from a field into a tail drain and associated farm infrastructure, not always entirely offsite into waterways.

A large proportion of the documents reviewed examined the interaction between cotton management practices and sediment transport, with the express purpose of determining management regimes to reduce offsite sediment transport. Incorporating rotation crops (e.g. sorghum, wheat) into a cotton monoculture coupled with minimum till maintained soil cover during the early stages of crop growth when the soil was susceptible to erosion resulting in a 70% reduction in erosion (Waters 2001). This is also similar to findings from dryland cotton production in the Fitzroy that found rotation crops and minimum till, through increased ground cover and soil water deficits reduced runoff and suspended sediments (Hulugalle et al. 2002). In another study, the retention of >50% ground cover in the form of either cotton trash or a previous rotation crop's trash (e.g sorghum, wheat), was found to greatly reduce sediment concentrations and soil losses. Whereas mulching of the trash or leaving the soil bare produced 3–4 times greater sediment concentrations in runoff than retained trash treatments (Silburn and Glanville 2002). Also, increased cover was more effective at reducing run off from furrows that had not been compacted by wheel traffic (Silburn and Glanville 2002).

In another study outside the GBR catchments, but on the predominant soil type for cotton cropping (Vertosol), furrows that had not been compacted by wheel traffic produced runoff, soil loss and sediment concentrations from rainfall which were 37, 59 and 33% less than from furrows compacted by wheel traffic (Silburn et al. 2013b). These studies show the importance of controlled traffic in reducing compaction and consequently runoff. The addition of polyacrylamide (PAM) to irrigation water was also an effective management tool to reduce soil loss and sediment concentrations in irrigation runoff water by acting as a flocculant so that soil particles were deposited out of suspension before leaving the field. PAM added to irrigation water reduced suspended sediment loads by 80% compared to conventional cotton cropping (Waters 2001). Other ways that have been investigated and were successful at reducing offsite movement of soil from cotton fields include sub-surface drip irrigation (McHugh et al. 2008), vegetative strips in irrigation channels (Waters 2001), sediment silt traps before drains (Connolly et al. 1999) and riparian vegetation adjacent to waterways (Lovett et al. 2003).

Nutrients

Nitrogen is generally applied both pre-season and in-season as a split application, while other nutrients (e.g. P, K, Zn and S) are applied once. Nitrogen fertiliser was applied at 181.2 kg N/ha pre-season with an additional

77 kg N/ha applied in season, for a total of 258.2 kg N/ha annually in 2019–20 in central Queensland (CRDC 2020a). The two main forms of N fertiliser applied to cotton are anhydrous ammonia and urea. Anhydrous ammonia has the potential to be volatilised if not applied deeper than 15 cm. Urea can be applied via irrigation water, side-dressed or broadcast, and each has its own management and soil conditions to avoid excess losses. These are highlighted in the cotton industries NUTRIpak, which forms part of myBMP (CRDC 2018). Other nutrients applied to cotton include P, K, Zn and S at rates of 33.6 kg P/ha, 41 kg K/ha, 2.1 kg Zn/ha and 7.6 kg S/ha respectively as reported for the central Queensland region in 2019–20 (CRDC 2020a).

The 2020 survey (n=13) also reported a N-use efficiency (NUE) of 9.2 kg lint/kg N. This is below the reported 13–18 kg lint/kg N (CRDC 2018) that is generally used to denote efficient N use in cotton, but marginally above the minimum NUE of 9 kg lint/kg N, proposed by Antille and Moody (2021) to indicate increased risk of N loss. However, it should be noted that a larger survey size over multiple years would be required to calculate a representative NUE for cotton farms within the GBR catchments. Regardless of this cotton crops take up approximately 180 kg N/ha (range 67–403 kg N/ha) (Rochester 2007), however only approximately 33% of N applied is recovered in the crop, about 25% remains in soil organic matter and 42% is assumed lost from the system via denitrification, leaching or runoff (CRDC 2018).

Measurements of nutrient losses in cotton in the GBR catchments are limited to the Emerald region of the Fitzroy. In a furrow irrigated cotton trial in the Emerald Irrigation Area where 250 kg N/ha was applied in three applications, N losses in runoff of 18.63 and 11.32 kg N/ha in two consecutive years were recorded (McHugh et al. 2008). Optimisation of the furrow irrigation system in the second year resulted in lower N losses in runoff. Furrow irrigation resulted in more than five times greater N losses in runoff than subsurface drip irrigation. In the same trial, P applied preplant at 25 kg P/ha resulted in P runoff losses of 778 g/ha from furrow irrigation, which was greater than all subsurface drip irrigation treatments. The majority of N and P losses were related to irrigation and not rainfall events due to low rainfall over the study period.

In contrast to the above study, another furrow irrigated cotton trial in the same region found higher TN and TP losses in rainfall events than from irrigation events (Waters 2001). Mean concentrations of TN and TP in runoff over two years from conventional furrow irrigated cotton, including both irrigation and rainfall events was 9.15 and 1.1 mg/L, respectively.

In a separate furrow irrigated cotton study in the same region four locations (input channel, furrow, tail drain and downstream weir) were sampled for TN and TP concentrations (Noble et al. 1996). TN concentrations in water entering the farm were below ANZECC guidelines of 750 µg/L for streams, but all three output locations sampled exceeded ANZECC guidelines, with median values ranging from 5775–12312 µg/L. TP concentrations also exceeded ANZECC guidelines at the same three locations as TN concentrations, with median concentrations ranging from 148–458µg/L.

Although the aforementioned studies reported TN and TP nutrient losses from cotton fields, losses were not reported as particulate N, particulate P or DIN, which are now often used when reporting on land management effects on the GBR. Due to the age of these studies (pre-2003) the applicability of the furrow irrigated management to current BMP practices is unknown and they may not provide total losses to waterways as some of the runoff may be recirculated or stored on farm. There was no reported nutrient loss information for north Queensland regions, although the NORpak (Cotton production and management guidelines for the Burdekin and north Queensland coastal dry tropics region) acknowledges the significant potential for N losses during the wet season and the need for timely application of fertiliser (Grundy et al. 2012).

Pesticides

The cotton industry has historically been heavily reliant on pesticides. However, with the introduction and widespread adoption of both Integrated Pest Management (IPM) and genetically modified (GM) cotton varieties in the late 1990s, the use of pesticides was significantly reduced. Indeed, in the cotton production and management guidelines for the Burdekin and north Queensland coastal dry tropics, it surmises the advent of GM varieties has allowed cotton to be grown in the region, which due to its proximity to the GBR would not normally be considered (Grundy et al. 2012). Genetically modified varieties that produce Bacillus thuringiensis (e.g. Bollgard II) reduce the need for spraying insecticides to combat a major cotton pest (e.g. Helicoverpa), while glyphosate resistant varieties (e.g. Roundup Ready Flex, Liberty Link) negate the need for long-lasting soil applied herbicides to control weeds.

Up-to-date data on regional pesticide usage (type and volume) across all cotton areas including GBR catchments is not freely available, however an annual audit is conducted by Crop Consultants Australia and is available for purchase online; Since this audit is not freely available it is not considered further in this report. In 2002, prior to widespread adoption of GM varieties the major insecticides used in the cotton industry included: dimethoate, amitraz, profenfos, Bacillus thuringiensis (Bt), chlorpyrifos, methomyl, pyrethroids and spinosad 41. The major herbicides used included: glyphosate, trifuralin, diuron, s-metalachlor, fluometuron and prometryn. The significant plant growth regulators included: dimethipin, oleyl alcohol, thidiazuron + diuron, endothall, mepiquat, thidiazuron, ethephon and sodium chlorate (Radcliffe 2002).

Although, pesticide usage and more specifically reducing pesticide use has been a focus of BMPs (CRDC 2020b; Maas and Redfern 2020), scant data on actual losses from cotton in GBR catchments was found in literature. Only one study was found that examined groundwater contamination from pesticides in cotton growing areas of the Fitzroy. The study found low levels of atrazine in bores, near Theodore, Biloela and Emerald, and concluded that widespread contamination of groundwater was unlikely, but due to surface water pesticide levels some monitoring should continue (Noble et al. 1996).

Concentrations of eight pesticides in runoff were examined from a conventional furrow irrigated cotton crop in the Fitzroy (Waters 2001). The two pesticides with the highest mean concentrations in runoff were diuron (39.16 ug/L) and endosulfan (2.94 ug/L). It should be noted that endosulfan was banned from use in Australia in 2010. The highest concentrations were found in runoff soon after application.

In another study in the Fitzroy, in a conventional furrow irrigated system, pesticide loads and concentrations in runoff were measured (McHugh et al. 2008). Pesticide loads averaged over two years were 983.29 g/ha for fluometuron, 373.91 g/ha for diuron, 276.41 g/ha for prometryn and 119.37 g/ha atrazine, while simazine (12.99 g/ha), dimethoate (350.98 g/ha) and endosulfan (289.50 g/ha) were only observed in one of the two years. Notably atrazine and diuron were not applied in the study season but were still measurable in runoff.

A separate but similar study in the same region measured the insecticide endosulfan and herbicides trifluralin, diuron, prometryn and fluometuron in soil and runoff from a cotton field (Simpson et al. 1998). Although there was found to be no soil build-up of pesticides each year, the highest risk of pesticide loss was early in the season soon after application when pesticide residues were still in the soil. A point of difference in this study was that they estimated losses of endosulfan of 3.6 kg a.i. from the tail drain to a river after a storm event late in the season. However, it was noted that this value would have been higher if the storm event had occurred early in the season when ground cover was lower.

These studies of pesticide runoff mainly report what leaves a cotton field, but only one study estimated pesticide exports off farm to a river system. Also, these studies were conducted in some cases 20 years ago and considering land management practices have changed in that time frame, the applicability of the data to current farm management practices is uncertain.

Bananas

Bananas are Australia's largest horticultural industry and highest selling supermarket product. It is estimated that Australian growers sold 388,000 tonnes of fresh bananas in 2017–18. Farm production of bananas reached $587 million and total economic contribution was about $1.3b and the industry employed 13,400 people (Australian Banana Growers’ Council, 2021).

Land used for banana production in the GBR catchment has increased from an average of 734 ha between 1965 and 1969 to 11951 ha between 2015 and 2019, which is an increase of 1628% (Lewis et al. 2021). This increase was larger than increases reported for sugarcane, cotton and other crops over the same time period. The majority of Australia’s bananas (> 90%) are produced in the north Queensland regions of Kennedy, Tully, Innisfail, Atherton Tableland, Mossman, Lakeland and Hopevale (Queensland Government, 2016). ABS data estimates that in 2019–20 banana plantations in GBR catchments occupied 11459 ha with > 99% being within the Wet Tropics NRM region. This compares to 12546 ha listed in the Australian tree crop map data. From both sources of data banana plantations occupied 0.03% of the total land area of the GBR catchment. The ABS estimates that 169 businesses grow bananas in the Wet Tropics, compared to 15 in other GBR NRM regions.

A number of plans and BMP resources relevant to banana production are available. The Wet Tropics Water Quality Improvement Plan 2015-2020 highlighted banana production as a focus for water quality second to sugarcane production (Terrain NRM, 2015). The plan highlighted a series of focus actions that could be implemented to have positive water quality outcomes. These include optimising fertiliser application via fertigation, use of slow-release fertilisers, use of permanent beds, block contouring and liaising to achieve recommended nutrient application rates. Industry body, the Australian Banana Growers Council, formulated the North Queensland Banana Industry Water Quality Strategy 2017-2020 (Australian Banana Growers’ Council, 2017). The goal of the Water Quality Strategy was to contribute to improved water quality of the GBR through BMPs, aiming at a 10% reduction in DIN and 5% reduction in sediment runoff. The Banana Best Management Practices – Environmental Guidelines for the Australian Banana Industry, includes a questionnaire so farmers can assess their practices against BMPs, which are outlined and explained (BMP first released 2013; version 2 available; DAF, 2016). In addition, chapter 12 of the Soil Conservation Guidelines for Queensland (Carey et al. 2015) lists general and specific guides on soil conservation in the horticulture industry including bananas. Reference to Bananas is also made in the Hort360 Reef Certification Interpretive Guideline (Growcom Australia, 2021). “Reef Assured – Bananas” is a recognised program for banana producers to demonstrate reef regulations (Freshcare, 2021).

Water

Banana plantations require ample and frequent water supply, therefore careful water management is needed as water deficits could adversely affect crop growth and yields. Being a long duration crop, the annual total water requirement is high, varying between 1200 mm in the humid tropics to 2200 mm in the dry tropics (FAO, 2021). In Queensland, even though the majority of banana farmers are located in the high rainfall Wet Tropics (annual rainfall ~ 3200 mm), most banana farmers still rely on irrigation for achieving high yield and quality. Banana plants are generally irrigated using micro-sprinklers. The use of trickle tape for irrigation of bananas is low.

In general, water utilization efficiencies (measured as fruit at 70% water content) in banana plantations vary from 2.5–4.0 kg/ha/mm for the plant crop and 3.5–6.0 kg/ha/mm for the ratoon crops (Carr 2009). ABS data indicate 85% of 'fruit trees, nut trees, plantation or berry fruits' in the GBR catchment, of which bananas are included, are irrigated (Table 9). Detailed publicly available information about water use and water use efficiency in the banana industry is limited.

For best banana production, water management aims at finding a balance between the soil's water content and the needs of the plant. The two main components are drainage, to eliminate excess water, and irrigation to make up for water deficits due to lack of rain or high evapotranspiration.

There are limited measurements of runoff and deep drainage from banana plantations in the GBR catchments. Bhattarai and Midmore (2015) reported water balances for bananas irrigated with drip and micro-sprinkler irrigation over three seasons in the Burnett Mary region. Crop water use accounted for 88 and 84% of the total water input in the drip and micro-sprinkler irrigation systems, respectively. Runoff was 9.0% (3.9 ML/ha) and 12.7% (6.0 ML/ha) of total water input for drip and micro-sprinkler irrigation respectively, while losses from deep drainage were less than via runoff and equated to 2.6% (1.1 ML/ha) and 3.1% (1.5 ML/ha), respectively. Results indicated that drip irrigation reduced water losses via runoff and deep drainage and that deep drainage events were found to be linked to large rainfall events and not irrigation events. Since this trial was done in the Burnett Mary overall water losses may be larger in the higher rainfall Wet Tropics. Indeed Armour et al. (2013) and Rasiah et al. (2010), in separate studies in the Wet Tropics, reported deep drainage losses of water inputs of 37–65% and ~38%, respectively.

Over the first three years of a five-year study at two sites with contrasting inter-row management regimes in the Wet Tropics similarly high deep drainage was recorded with 18–33% of annual rainfall plus irrigation being lost to deep drainage (Armour et al. 2012). Runoff from the same sites over the three years was ~13–44% of rainfall and irrigation (values extracted from graphs). Management that retained grass in the inter-rows between banana rows reduced runoff by 25–54% compared to when inter-rows were left bare (Armour et al. 2012). Runoff was only recorded during one of the final two years of the study and was substantially lower (~<8%) than other years due to lower rainfall (Masters et al. 2017). Similarly, deep drainage was also lower in the final two years ranging from 18 to 25% (data extracted from graph) of total rainfall and irrigation (Masters et al. 2017). It should be noted that runoff in the first three years of this experiment may be inflated due to headland drainage issues at one site.

A study of the microbial ecology of deep drainage water under banana crops recorded 41% of rainfall was lost as deep drainage, however, it was unclear from the publication whether this included water applied via irrigation as well (Wakelin et al. 2011). In a study comparing riparian buffer practices, runoff variability between rainfall events and between sites was very high with 1–65% of event rainfall being lost as runoff from four hillslopes cropped with bananas in the Wet Tropics (McKergow et al. 2004). Slopes at these sites varied between 3 and 13% and the hillslope area ranged from 0.2 to 5.0 ha. It was reported that the total event rainfall was the main determinant of runoff volumes in this study. Peak runoff discharges from the 5ha catchment were >350 L/s, which compromised the riparian buffer and diminished its performance. Further study is needed to assess the effectiveness of buffer strips on sloping tropical cropped land and identify its limitations.

It is evident from the reported data that deep drainage and runoff can be considerable losses in a water balance of banana cropping and is generally a higher percentage of total water inputs when those inputs are higher. Considering water is the transport agent for the movement of sediment, nutrients and pesticides off-farm, measuring and determining methods to reduce water losses is important in controlling these pollutant losses.

Sediment

Sediments are one of two pollutants identified in the Wet Tropics Water Quality Improvement Plan 2015-2020 as being of considerable focus for the banana industry (Terrain NRM 2015). When soil erosion and water surface runoff happen, sediments are brought into water bodies affecting water quality. Reef Protection Regulations targeting sediment losses were introduced in 2020 and aim to reduce sediment losses by maintaining 60% groundcover in inter-rows, growing cover crops/grass in fallows and implementing measures (e.g. contour banks, vegetation buffers) to stop runoff and sediment reaching water bodies (Office of the Great Barrier Reef 2019a).

Similar to other crop land uses, studies in north Queensland have shown that nutrients and sediments are exported from watersheds that contain banana plantations, particularly during wet season rainfall events (Bahadori et al.

2020, 2019; Brodie et al. 2012; Faithful and Finlayson, 2005; Hunter and Walton, 2008). A catchment wide study in the Johnston River Catchment in the Wet Tropics found that bananas had a similar per unit area suspended sediment flux (4.0 ± 2.5 t/ha/yr) to sugarcane cropping (3.8 ± 2.5 t/ha/yr), which is considerably higher than other land uses in the lower catchment (1.2 ± 1.1 t/ha/yr) (Hunter and Walton, 2008). Modelling TSS export loads in the Wet Tropics found that bananas contributed only a small portion to the total TSS export load and total TSS load from bananas was estimated at 28 kt/yr, ~ 4% of total TSS discharged in the area (Hateley 2014). However, similar to the suspended sediment flux reported from the Johnston River Catchment, across the whole Wet Tropics, banana plantations had the largest per unit area TSS export of 1.8 t/ha/yr (Hateley 2014). Bahadori et al. (2020) used combined isotopic (δ13C, δ15N) and geochemical (Zn, Pt and S) signatures and stable isotope analysis to estimate the contribution of different land uses to the sediment of the Johnstone River. Their results agreed with previous studies and indicated that banana plantations contributed the largest proportion of sediments to the coast per unit of area. Overall contribution to the suspended and bed sediments in the river estuary were 26.7 and 20.4%, respectively (Bahadori et al. 2020).

Modelling approaches have also attempted to determine the effects of improving management practices on the export of sediment from catchments containing banana plantations. Armour et al. (2009) simulated sediment loads in the Tully-Murray catchment of the Wet Tropics, using a long-term, annual-average catchment biophysical model (SedNet/ANNEX). Model simulations resulted in an 18% reduction in sediments, using a combination of improved cultivation and fertiliser management of sugarcane and bananas and restoration of the most degraded riparian areas. However, no information about the relative contribution of banana plantations is mentioned in their simulations. In a similar approach using the SedNet model simulations, Hateley et al. (2020) estimated that improved management of sugarcane and bananas resulted in a reduction of 10% (144 kt/yr) in suspended sediment export to the coast and 14% in hillslope erosion. The highest sediment generation per unit was produced by sugarcane and banana land use (110 t/km^2).

Field studies located in the Wet Tropics have reported losses of suspended sediment and bedload sediment. In a field study over one year, Faithful and Finlayson (2005) measured sediment losses from banana plantations and reported minimum, maximum and median TSS concentrations in runoff of 2, 7250 and 75 mg/L respectively. The high TSS concentrations in the runoff were attributed to higher slopes and a greater proportion of exposed ground surface during the wet season. In one storm event 126 kg TSS/ha was estimated, but this was said to likely be an underestimation due to sampling techniques.

Masters et al. (2017) reported large TSS losses from two banana sites with differing inter-row management practices. Bare inter-rows lost 1–11 t/ha of soil annually in runoff. One large rain event caused 285 kg soil/ha to be lost from bare inter-rows, however 290 kg soil/ha was also lost from grassed inter-rows due to difficultly in maintaining the grass cover in the heavily trafficked inter-rows. Annual sediment losses were found to be greater in years with higher annual rainfall and subsequently higher surface water runoff.

Over three wet seasons across four banana sites with differing catchments and riparian buffers soil loss amounted to <1 to >70 t/ha per wet season (McKergow et al. 2004). This loss was bedload sediment which predominately consisted of 2–4 mm diameter soil particles and aggregates. Suspended sediments were not sufficiently measured in this study to calculate overall losses.

Nutrients

There is a general view that bananas have a very high requirement for N and K, and that frequent applications of N and K are required since it does not accumulate in the plant (Prasertsak et al. 2001). Bananas require relatively high fertiliser rates as high yielding banana crops extract large quantities of nutrients from the soil (Lindsay et al. 1998). On average, every tonne of banana fruit removes about 8 kg N, 1.5 kg P, and 25 kg K from the soil (SMART Fertiliser Software, 2020). That is equivalent to 240 kg N, 45 kg P and 750 kg K, assuming a banana yield of 30 t/ha.

In addition to N, P and K, banana plants also need many other nutrients, such as sulphur, magnesium, zinc, calcium and copper (Lindsay et al.,1998). Among all nutrients, N and P are considered the main nutrients of focus that can affect water quality in the GBR and of those DIN and PN have been identified as the main nutrients of concern for the banana industry (Terrain NRM, 2015).

Nitrogen and P fertilizers are normally applied by surface banding and/or fertigation application methods. Regulations by the Queensland Government indicate that N fertiliser must only be applied to the plant row and not the inter-row and ground-based broadcast of P fertilisers can only be applied in a plant crop and only when it can be incorporated into the soil within three days of application (Office of the Great Barrier Reef, 2019b). Historically more than 500 kg N/ha/yr was applied for bananas grown in Australia (Food and Agriculture Organization of the United Nations 2021). Average industry N application rates have decreased by as much as 40% from 520 kg N/ha/year in 1995 to 315 kg N/ha/year in 2010 (Armour, 2018). According to a survey reported by Sing (2012), the average N application rate in the banana industry is ~290 kg N/ha/yr and half the production area received 251–300 kg N/ha/year. Application rates for P fertilizer vary from 0 to 60 kg P/ha/year. Under Queensland Government regulations, banana farmers within the GBR region are required to apply N up to a threshold level of 280 kg N/ha for a plant crop and 400 kg N/ha for a ratoon crop, then justify any higher application through a nutrient management plan informed by leaf sampling. Similarly, P application has a set threshold rate of 60 kg P/ha and if more P is applied a nutrient management plan must be developed (Office of the Great Barrier Reef, 2019c). A soil Colwell-P concentration of 45 mg/kg has been suggested as optimal for banana cropping (Masters et al. 2017).

The Council of Agriculture, Science and Technology, suggests that, in general, fertilizers are not utilized efficiently in agricultural systems, and plant uptake of fertilizer N seldom exceeds 50% of the N applied for most crops (Council of Agricultural Science and Technology 1992). Lindsay et al. (1998) noted that the two nutrients most readily lost in banana growing are N and K. In a banana 15N macroplot study Prasertsak et al. (2001) reported 25% of N applied as urea was lost from the soil-plant system 40 days after application, with 15% utilised by the plant and the remaining (60%) still in the soil. The large N component remaining in soil was still prone to loss from the system after the 40 days. Therefore, N applied to banana cropping has the potential to be lost through numerous pathways such as runoff, denitrification and in particular for nitrates, deep drainage (Armour et al. 2013).

As summarised by Armour (2018) nitrate is the major form of N loss, as N from N fertilisers is rapidly transformed to nitrate by soil bacteria. Nitrate is highly mobile and easily lost from the soil via runoff and deep drainage. Urea volatilisation and nitrate denitrification are other loss pathways but with little effect on water quality. Nutrients can also be lost through soil erosion, either through wind or flood water. There is evidence that the risk of fertiliser loss in runoff is directly proportional to the fertiliser application rate from Australian sugarcane farms (Fraser et al. 2017) and this would be true as well for banana farms. Research in Wet Tropics catchments have found nitrate concentrations in water bodies are strongly correlated with fertilised land uses (mostly sugarcane and bananas) (Mitchell et al. 2009). A small increasing trend of nitrate under low flow conditions was observed over 13 years in the Tully river from 1987 to 2000 (Mitchell et al. 2001). The authors surmised that this could have been due to increasing fertiliser use and agricultural expansion over the same period. Particulate N also increased over the same period, possibly caused by increased erosion in the catchment. This indicates a link between agriculture and N in water ways, however this data is outdated and an updated assessment under more recent conditions is required. Hunter and Walton (2008) modelled N and P loads from land uses in the Johnston River system over 39 years and found 42 kg N/ha/yr and 6.8k g P/ha/yr were exported from banana lands. The loads were highly variable between years and P was dominated by sediment P (81%). Other modelling of the whole Wet Tropics region found bananas contributed a small portion to the total N and P export load in the Wet Tropics NRM region, however they exhibited the largest per unit area exports of TN (25 kg/ha/yr) and TP (3.1 kg/ha/yr) (Hateley 2014). A review of nutrient concentration data in runoff in Australia listed banana land use as the third highest for both TN and TP with median concentrations of ~2,700 µg/l and 1,400 µg/l, respectively, however this was based on data from only four sites (Bartley et al. 2012).

Water movement in banana plantations creates surface runoff and deep drainage with large quantities of water moving through and over banana soils in the Wet Tropics, by either heavy rainfall or irrigation. For example, in the Innisfail-Tully area, runoff from blocks is typically 500–900 mm/year and can erode productive topsoil, and deep drainage below the rootzone typically ranges from 800 to 1,400 mm/year, meaning that leaching of N through the soil profile can be an important loss pathway (Rasiah et al. 2010). In research conducted by Armour et al. (2014) it was reported that nutrient concentrations in on-farm runoff water were low, however considerable nitrate-N was moving through the root zone. Much of this nitrate moves in a large pulse after significant rainfall and reduces to low concentrations quite rapidly.

In a study located at South Johnstone in the Wet Tropics Armour et al. (2014) reported that loads of N in deep drainage were 23–48 kg N/ha for the banana plant crop over a range of fertiliser rates and types. These high loads were attributed to very high levels of soil mineral N at planting (165 kg N/ha in the top 0.6 m of soil), which was caused by cultivation of the pre-existing pasture on the site prior to planting. In contrast, soil mineral N was very low at the start of the ratoon crop, which influenced the recorded ~1 kg N/ha lost in deep drainage over the ratoon crop. The low soil mineral N at the start of the ratoon crop was due to plant uptake and losses incurred during the plant crop. The authors recommended further studies in ratoon crops to confirm deep drainage losses before making recommendations. No differences in N in deep drainage were evident between the different forms of fertilisers and rates of N applied. Their results indicated a moderated application rate of N fertilizer can significantly reduce the N loss through deep drainage. In another field study in the Wet Tropics N fertilizer loss in deep drainage was 246 and 641 kg N/ha over 2 crop cycles, which was 37 and 63%, respectively of the applied N. Rates of applied N were very high at 710 and 1065 kg N/ha, respectively which is larger than recommended rates of N (Armour et al. 2013).

Rasiah et al. (2010) investigated if any linkage existed between nitrate-N in leachate collected at ~1 m depth under banana and that in groundwater and drain water, using samples collected at short intervals during three consecutive rainy seasons (January–July) from a ~300-ha banana farm in the Tully River catchment. The mean nitrate-N concentrations in leachate, groundwater and drain water were 5320, 4135, and 1976 µg/L, respectively.

Significant positive relationships existed between rainfall received and leachate volume collected, and between leachate volume and nitrate-N concentration. It was concluded the unused/under-utilised nitrate that leached below the root-zone was imported into groundwater by the percolating rainwater and was exported into the drain via groundwater base-flow discharge. Rasiah and Armour (2001) found large quantities of nitrates leached below the crop root-zone and accumulated at depth under long-term banana cropping. Nitrate-N concentration was 6.9 mg/kg and nitrate-N load in the top 10 m of soil was 145 kg/ha, nearly 7 times of the value under rainforest (21 kg/ha).

Masters et al. (2017) reported annual DIN loads in deep drainage ranged from 0.3–4.6 kg/ha at two sites over five years in the Wet Tropics. The major contributor to DIN load was oxidised-N. Overall, the DIN concentrations monitored in deep drainage at both sites were consistently low, resulting in much lower loads than have previously been reported for Wet Tropics' banana cropping. Total N lost annually in surface runoff ranged from 3–60 kg N/ha/yr and most (82–91%) of the N was in the particulate form. It was reported that TP losses ranged from 2–26 kg P/ha/yr, primarily in the particulate form (>97%) and associated with erosion losses.

Management practices to mitigate nutrient losses from banana plantations have been trialled in the Burnett Mary and Wet Tropics regions. In the Burnett Mary it was found that irrigation method can have a significant influence on nutrients lost by surface runoff and deep drainage. In a 3-year trial, Bhattarai and Midmore (2015) demonstrated that 22.3% of total soil N and applied fertilizer N was lost through surface runoff and deep drainage when drip irrigation was used, compared with 33.5% for micro-sprinkle irrigation. Riparian buffers were assessed in the Wet Tropics where McKergow et al. (2004) reported that riparian buffers were able to reduce TN and TP loads leaving banana plantations over three wet seasons. Loads leaving banana fields before entering riparian buffers ranged from 1.22 to 9.72 kg N and 0.69 to 3.8 kg P. The highest loads were recorded at the site with the steepest slope (13%) and largest catchment area (5 ha).

Pesticides

There are many different agrichemicals used in the banana industry for controlling pests, fungi and diseases. More than 100 different pesticides are registered for use in the banana industry in Australia (Hort Innovation 2020). Hort Innovation lists these chemicals and highlights the regulatory threats to agrichemicals currently approved for the management of the pests and diseases in bananas, as well as current initiatives aimed at addressing identified pest management deficiencies.

Even through pesticides are regarded as one of three priority pollutants in the GBR catchment, pesticides are not identified as a high priority pollutant from banana production in terms of the relative impact on water quality entering the Great Barrier Reef (Terrain NRM 2015). This is because residual herbicides are only occasionally used and those chemicals that are frequently used (insecticides and fungicides) are generally only used in small quantities with a very targeted application (Terrain NRM 2015). In the 2015–20 Wet Tropics Water Quality Improvement Plan, it is estimated that pesticide use has reduced by as much as 90% in the last 20 years (Harvey et al. 2018).

Limited research has been conducted on the fate of pesticides applied to banana plantations. It was found by Shaw et al. (2010) that nearly all pesticides detected using passive samplers in river mouths and reefs near the Wet Tropics, were registered for use on sugarcane and/or banana crops, however apportioning pesticides to individual commodities was not possible. Bainbridge et al. (2009) reported pesticide residues were not detected in the banana land use category. However, they attributed these undetected levels in banana plantations to the diluting effect from nearby forest land.

Lewis et al. (2014) reported the results of a three-year study on the fate of three pesticides commonly used in banana production. The findings showed that six months after application, two herbicides (glyphosate and glufosinate) were detected in surface runoff and glyphosate was occasionally detected in deep drainage. The fungicide mancozeb was below detection limits in both surface runoff and deep drainage samples. Masters et al. (2015) conducted a two-year study investigating the fate of two herbicides Basta (applied at 4668 g/ha/yr) and Glyphosate 450 (applied at 2250 g/ha/yr) and one fungicide mancozeb (reported as Penncozeb 75DF; applied on a fortnightly basis at 3.33 kg/ha). Of the 29 samples collected in 2011–12 (over 13 rainfall runoff events) and 13 samples in 2012–13 (2 rainfall runoff events), Glyphosate and its metabolite aminomethylphosphonic acid, and glufosinate were frequently detected in both years and EMCs of glyphosate ranged from 0.12–2.5 µg/L. Glufosinate was only present in runoff for a short time after each application, peaking at 6.3 µg/L. During the 2011–12 runoff events, total glyphosate lost in runoff was 1% of the active ingredient applied. In the following wet season (2012–13 runoff events), the total glyphosate load in runoff was much lower, representing 0.1% of the applied. The load of total glyphosate lost in deep drainage was similar to that lost in runoff which was <0.1% of the applied.

Bagshaw and Lindsay (2009) claimed that improved integrated pest management not only reduced nematicide use but also potentially reduced sediment and pesticide transport in runoff water by reducing the number of pesticide applications required and providing ground cover during fallow periods, however no detailed information is available.

Table 12: Estimated number of businesses growing orchard fruits, nuts and plantation fruit according to Natural Resource Management Regions in the Great Barrier Reef catchment (ABS 2021b).

Commodity	Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Total
	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.
Nuts													
Macadamias	117		1		1	*	-		7	**	-		126
All other nuts	4	^	-		-		-		-		-		4
Orchard Fruit													
Apples	1	*	-		-		-		-		-		1
Avocados	91	^	3	^	1	*	1	*	75	^	1		174
Mandarins	53		13	**	1	*	3	*	-		-		70
Mangoes	46	*	9		4	^	86	^	46	*	-		191
Nectarines	12	**	-		-		-		-		-		12
Olives	1		-		-		-		-		-		1
Oranges	20	^	2	^	1	*	3	*	-		-		25
Peaches	13	**	-		-		0		-		-		13
All other orchard fruit	88	^	10		5	*	14	^	105	^	2	^	226
All orchard fruit (including nuts)	294		27	*	8	*	93	^	188	^	2	^	612
Plantation fruit													
Bananas	10	*	-		2	^	2	^	169		1	*	185
Pineapples	24	^	17		1	*	1		10	**	0		53

No. Estimate of number of businesses; RSE Relative Standard Error; ^ estimate has a relative standard error of 10% to less than 25%; * estimate has a relative standard error between 25% and 50%; ** estimate has a relative standard error greater than 50%. There are no calculated RSEs for row totals. The sum of businesses may not equal the total number of businesses as a business may grow more than one commodity.

Macadamias

There are about 13,381 ha of macadamia orchards in the GBR catchment, with 12,695 ha in the Burnett Mary region, 459 ha in the Fitzroy region, 125 ha in the Mackay Whitsunday region and 102 ha in the Wet Tropics (Table 3), with general industry trends (2009–19) by region outlined in an industry benchmark report (State of Queensland, 2020). It was estimated in 2019–20 that there were 117 growers in the Burnett Mary and 7 growers were in the Wet Tropics (Table 12). This shows a possible discrepancy between the spatial and survey data, with only one grower recorded for the Fitzroy and Mackay Whitsunday regions. Macadamias grow well in well drained and moderately acidic soils, with an optimum pH (water) range between 5 and 6 (Wehr and Smith 2016). Fertiliser N application rates used by growers in the catchment remain to be surveyed, however they are suggested to range from 30 to 150 kg N/ha fertiliser N each year, based on recommendations of 27–82 kg N/ha/year (O’Hare et al. 2004) and the amount of 150 kg N/ha/year used in a field trial in NSW (Reid 2002). Macadamia trees can tolerate low P in soil, and thus fertiliser P is not always required. Overuse of fertiliser N can cause excessive vegetative growth, and too much fertiliser P can induce deficiency of Zn and Fe due to Zn-P and Fe-P precipitation in soil and plant cells, whilst posing a threat to water quality as observed in field studies (see below).

General best management practices for macadamia farming have been elaborated by O’Hare et al. (2004) and Bright et al. (2016); tree crops are also referred to within the Hort360 reef certification management practices, with case studies showcasing best practice soil management benefits, including utilisation of mulch and harvest trash in some regions (Growcom, 2021). Groundcovers through growing grass in the inter-row space and using mulches in the tree row can effectively reduce soil erosion (Reid 2002; Cox et al. 2010). However, trees in mature macadamia orchards generally have dense canopies, which generate low light conditions and thus make it difficult for most groundcover species to survive. Wide row spacing combined with tree canopy management (hedging and tree height control to ≤6 m) can be used to maintain inter-row gaps for light penetration to help grasses to establish and thrive (Wehr and Smith 2016). Shade-tolerant species such as sweet smother grass (*Dactyloctenium austale*) are recommended as groundcover in macadamia orchards (Firth and McFayden 1999; Reid 2002). Field trials are being conducted for macadamia nut harvesting where the nuts are directed away from the soil-roots at harvest time with the use of shade cloth structures. Preliminary results suggest that this technique may have benefits of increasing productivity, retaining organic matter, improved water use efficiency and reducing soil erosion (ABC News, 2021).

Leaf and soil analyses are useful techniques to help determine fertiliser N and P application rate and time. Recommended foliar N concentrations for high yielding orchards (4.5–5 t nuts in shell/ha) in Queensland are 1.4–1.5% (O’Hare et al. 2004), while foliar P concentrations should be maintained in a range between 0.08–0.10% (O’Hare et al. 2004; Wehr and Smith 2016). The optimum soil Cowell-P content is about 85 mg P/kg for most macadamia soils, but >100 mg P/kg may be required for soils with strong P-fixing capacity such as Ferrosols (O’Hare et al. 2004). Split applications of the nitrogenous fertiliser (>3 times per year) can help ensure sustained N supply through the plant growing season, whilst avoiding excessive N supply following fertilisation that may result from fewer applications (O’Hare et al. 2004; Wehr and Smith 2016).

It is also recommended that soil available P and leaf P content should be monitored regularly, to ensure P fertiliser is applied only when required. The largest losses of dissolved inorganic phosphorus (DIP) throughout a year generally occur shortly after P fertiliser application (Hart et al. 2004). As DIP is most ‘bioavailable’ among all P forms, soluble P fertiliser is recommended to be applied at a right time to minimise DIP loss through runoff and subsequent pollution to waterbodies.

Pesticides registered for use in managing macadamia pests and diseases as well as BMP for application of pesticides are outlined in the annual Macadamia Plant Protection Guide (NSW DPI, 2021). There are approximately 20 pesticides listed to control 16 macadamia pests.

Water

As macadamia crops are mostly grown in high rainfall regions (> ~1,000 mm per year), overland water flow during intense rainfall events can cause severe runoff and soil erosion, particularly in orchards on slopes and/or with bare ground in the inter-row area. The runoff volume in each rainfall event varies with soil water content, infiltration rate, slope, and rainfall intensity and duration. Irrigation is a common management practice used by macadamia growers in the GBR catchment, particularly in regions where annual rainfall is <1,200 mm (e.g. Burnett Mary region) or where the rainfall events are unevenly distributed throughout the year. Up to five megalitres of water/ha/year are used for irrigation on mature trees in the Burnett Mary region (O’Hare et al. 2004). Macadamia orchards are irrigated generally with water-efficient techniques such as sprinkler or drip irrigation, which seldom causes substantial irrigation water loss.

Field measurements of water runoff loss in the GBR catchment are few and only one study in the Burnett Mary region (Stork et al. 2009) was found in the literature. Field measurements were conducted on a farm with a 3.1% slope in the Burnett region over 13 months. Five runoff events were recorded between October and July in the next year, when 709 mm of rainfall and 458 mm of irrigation were received in total. The total volume of surface flow amounted to 177 m^3/ha (0.177 ML/ha), accounting for 5.3 ± 1.1% of the five episodic rainfall events received.

A study in northeast NSW was conducted in a mature macadamia orchard on a Ferrosol with a 5-degree slope and bare or turfed inter-row over a 3-year period from 1999 to 2002 (Reid 2002). On average, 12% of the total rainfall volume (13.2 ML/ha/year) was lost as runoff in the plot with bare inter-row. Only 0.7% of the total precipitation was lost as runoff in events of <150mm rainfall, while up to 70% of rainfall could be lost in events with >150 mm. The plot with sweet smother grass grown in the inter-row area reduced water runoff by 60% on average in <150 mm rainfall events and by about 10% in >150 mm events (Reid 2002).

Sediments

Macadamias are harvested mechanically using equipment fitted with powerful blowers or sweepers. The blowing and sweeping processes disrupt and displace the surface soil, which accentuate the risk of subsequent movement of the detached soil in future high rainfall events.

Sediment losses from the above-mentioned macadamia farm with grassed inter-rows in the Burnett Mary region was estimated to be 5.7 kg/ha/year, based on the particulate N loss of 159 g/ha and sediment total N content of 2.81% (Stork et al. 2009). No other measurements were found on sediment loss from macadamia orchards in the GBR catchment.

Measurements in a macadamia orchard with bare ground in NSW (Reid 2002) found that total soil erosion loss was about 2,000 kg/ha/year on average, with sediment and suspended solids accounting for approximately 97% and 3% of the total soil loss. The turfed plot decreased total soil loss by 99.9% compared to the plot with bare-inter-rows.

Nutrients

The literature search found only one study (reported in two separate papers) on N or P losses from macadamia farming in the GBR catchment (Stork et al. 2009, 2012), as briefly described above. The trees received N fertiliser as ammonium potassium sulphate broadcast on the plant beds periodically (rates not given), P fertiliser as triple superphosphate in July 2006, and irrigations with micro-jet sprinklers. Runoff occurred when the storm intensity and duration exceeded 20–40 mm/h for >9 minutes. The annual N losses amounted to 0.28 kg N/ha/year, with particulate N in sediments accounting for 56%, while the dissolved organic and inorganic N (DON and DIN) contributing 18 and 26%, respectively (Stork et al. 2009). The annual total P losses were 0.35 kg/ha, with dissolved inorganic P (DIP) representing 88% of all P losses, which was attributed to excessive and untimely P fertiliser application (Stork et al. 2012)

In the 3-year field study in NSW (Reid 2002), average annual N loss from the bare inter-row plot applied with 19–47 kg N/ha/year amounted to 12.9 kg N/ha, with 10.4 kg N/ha in sediments and 2.5 kg N/ha in runoff, respectively (recalculations from the reported data). With P fertiliser applied at 4.2–37.5 kg P/ha/year, the average Bray P (total P not reported) loss was 0.8 kg P/ha/year, with 0.2 kg P/ha in sediments and 0.6 kg P/ha in runoff. The turfed plot decreased total N and Bray P losses in the runoff suspension by 36 and 46%, respectively (recalculations from Reid, 2002). Growing grass reduced total N loss in sediment and runoff by 88% compared to the bare-inter-row plot.

Pesticides

Only one report (Stork et al. 2007) was found on pesticide losses from macadamia farming systems in Queensland. Following two commercial applications of the insecticide endosulfan at the recommended rate and five episodes of runoff caused by varying storm intensities in a macadamia orchard in the Burnett Mary region, no presence of the insecticide and its metabolites was detected in the sediment and runoff samples.

Avocados

There are about 6,530 ha of avocado orchards in the GBR catchment, with 3,938 ha in the Burnett Mary region, 2,492 ha in the Wet Tropics and 99 ha in the other four regions (Table 3). It was estimated in 2019–20 that the Burnett Mary and Wet Tropics had 91 and 75 growers respectively (Table 12). As these regions mostly have an average annual rainfall of > 900 mm, rainwater and sediment loss can occur in high rainfall events, particularly from farms on slopes and/or with bare inter-rows.

Best management guidelines are available for Queensland avocado growers (DAF Queensland 2013a; b). The Best Practice Resource of Avocados Australia has plenty of useful information that can be accessed online for free by registered users (https://avocado.org.au/best-practice-resource/). Tree crops are also referred to within the Hort360 reef certification management practices.

Nitrogen-efficient management techniques such as fertigation and the 'little and often' approach (multiple applications at low rates with short intervals) are commonly adopted in avocado farming. These techniques can effectively reduce the risk of N loss into streams and subsurface water through runoff and leaching. In addition, avocado growers should conduct leaf sampling and analyses one to two times in autumn and early summer each year (Newett *et al.* 2018), which can effectively help identify nutrient deficiency or oversupply. The optimum leaf N content for bearing trees ranges from 2.2 to 2.6%. Within this range, the recommended N application rate is 110 kg N/ha/year (DAF Queensland 2013b), which can be adjusted up or down based on leaf N content, leaf colour, canopy health, crop load and soil texture and mineral N contents.

Phosphorus fertiliser is often not required or is needed at only relatively low dosages (0 to 100 kg P/ha/year with an average rate of 31 kg P/ha/year; Newett et al. 2018). Over-fertilisation with P can cause nutrient imbalance by fixing trace elements such as iron and zinc and thus lead to productivity loss. Annual leaf analysis and soil tests every 2–3 years can help identify the needs for P fertiliser application. The current optimum range of leaf P contents used in Australia is 0.08–0.25% for autumn samples (DAF Queensland 2013b), which is much wider than the optimum range of 0.15–0.18% recommended in California (Crowley and Campisi 2016). If soil available P and leaf P contents are adequate (e.g. soil Cowell P = 30–60 mg P/kg), there would be no need to apply P fertilisers. In cases where soil or leaf P contents are lower than the recommended levels, P fertiliser should be applied in bands on a relatively regular basis to minimise P fixation, particularly for soils with high P-fixing capacity, such as Ferrosols and Podosols.

Water

Avocado orchards are generally irrigated in Queensland. The amount of irrigation water used largely depends on the annual rainfall and evaporation, ranging from 6 to 8 ML/ha/year in far north Queensland (e.g. Atherton and Mareeba) to 8 to 12 ML/ha/year in the Burnett Mary region (DAF Queensland 2013a). The variability in rainfall greatly affects the irrigation required as evidenced by other estimations of irrigation requirements for the Burnett Mary region, being lower in comparison at 5–7 ML/ha (Growcom, 2021). Mini-sprinklers are most commonly utilised for irrigation purposes, followed by drippers. Soil moisture is monitored throughout the season by almost all growers using various techniques (Newett et al. 2018). With these techniques in practice, the risk of irrigation water loss from runoff should be very low. However, rainwater loss through runoff can occur in high rainfall events, particularly in the Wet Tropics, although no field measurements have been found from the literature search.

Sediments

No measurements of soil erosion and sediment loss from avocado orchards in the GBR regions have been found. Unlike macadamia, manual avocado harvesting does not cause as much mechanical disturbance to the soil surface. Thus, the risk of sediment loss from avocado orchards should be lower compared to macadamia orchards. However, ground cover with grass in the inter-row area should help minimise potential sediment loss from orchards on slopes in high rainfall regions.

Nutrients

Nitrogen fertilisation plays an important role in maintaining avocado productivity and quality. Based on a national survey involving 34 growers (16 from Queensland), N fertiliser was applied at 69–528 kg N/ha/year (Newett et al. 2018). The average application rate was 212 kg N/ha/year, which is about two times the recommendation of ~110 kg N/ha/year for normal mature trees in the Best Practice Resource (DAF Queensland 2013b). Therefore, excessive fertiliser N use may be a widespread practice in the industry. Based on the above N application rate, the total amount of fertiliser N use on avocado farms in the GBR region is estimated to be approximately 1384 t N/year, which can be potentially decreased to 653 t N/year with the recommended N rate.

No measurements of N loss from avocado orchards in the GBR regions have been found from the literature. Despite the wide adoption of N-efficient application methods, substantial N runoff may occur following high rainfall events, particularly on farms where excessive amounts of fertiliser N were applied. In addition, avocado trees are generally grown on well drained soils, due to their vulnerability to the root disease *Phytophthora*. Therefore, some avocado orchards may have higher risks of N loss through leaching than other cropping systems on poorly drained soils or in drier areas, particularly in the orchards applied with more than the recommended N rate of 110 kg N/ha/year.

The risk of P loss from avocado orchards into waterways is relatively low compared to N loss. Apart from the much less soluble/mobile nature of P compounds in soil, nil or low P fertiliser application rates (31 kg P/ha/year on average; Newett et al. 2018) required for avocado trees help prevent substantial P loss into waterways. Over application of P fertiliser can seriously affect tree growth and productivity, thus should be avoided. Field studies on P loss through leaching or runoff appeared to be absent in the GBR regions.

Pesticides

Numerous pesticides and fungicides are used by avocado growers to control pest insects, diseases and weeds. However, no record of field studies on pesticide loss from avocado orchards in the GBR region were reported from the search literature criteria.

Vegetables

Vegetables account for 0.04% or 18,142 ha of the GBR catchment according to ABS data from 2019–20. The three NRM regions with significant areas of vegetable production are the Burnett Mary (6,665 ha), Burdekin (10,283 ha) and Wet Tropics (962 ha) regions. Sixty percent of Queensland's vegetable production is in the GBR catchment (Harper 2014). Vegetables are the most diverse commodity group classified in this report. There are 33 vegetable crops listed in the Australian Horticulture Statistics Handbook 2019–20 and 13 of those have major Australian production areas within the GBR catchment (Table 13) (Hort Innovation 2020).

Vegetable systems are mostly characterised by short growing seasons (e.g. a few months), compared to other broadacre and tree crops, and require soil moisture to be maintained in the optimum range throughout the season to produce quality products. These factors have implications for the management of the cropping cycle with multiple cropping opportunities annually of the same crop or different crops, as well as the opportunity to be grown in rotation with other perennial crops (e.g. sugarcane). Due to the need for constant optimum soil moisture conditions irrigation is applied frequently by various methods depending on crop type, region and water access.

According to ABS data there were an estimated 424 businesses growing vegetables in the GBR catchment in 2019–20 (Table 14). Burnett Mary contained the most businesses, with 213, followed by the Burdekin with 107 and the Wet Tropics with 86. Excluding the 'other vegetables' class pumpkins (96), potatoes (73) and melons (65) were grown by the most businesses.

The vegetable industry is included in the Hort360 BMP program administered by Growcom. Hort360 consists of 13 modules with those relevant to water quality impacts being irrigation, pesticide, soil, climate, runoff and nutrient modules. The Soil Conservation Guidelines for Queensland includes a chapter on horticulture which specifically references vegetables and how to manage runoff in these systems (Carey et al. 2015). The Queensland Department of Agriculture and Fisheries (DAF) have also produced guides for specific vegetables, including, sweet corn, capsicum, chilli, tomato, potato and sweet potato which outline BMP, although they are over 10 years old (Fullelove et al. 1998; Jackson et al. 1997; Loader et al. 1999; Meurant et al. 1999; Wright et al. 2005).

Table 13: Vegetable crops with major Australian production areas in the Great Barrier Reef catchment (Hort Innovation 2020).

Vegetable	NRM regions
Beans	Burnett Mary, Wet Tropics
Capsicum	Burnett Mary, Burdekin
Chilli	Burnett Mary, Burdekin
Cucumber	Burnett Mary, Burdekin
Eggplant	Burnett Mary, Burdekin
Leaf Asian vegetables	Burnett Mary
Peas	Burnett Mary
Potato	Burnett Mary, Wet Tropics
Pumpkin	Burnett Mary
Sweet corn	Burnett Mary, Burdekin
Sweet potatoes	Burnett Mary, Burdekin
Tomatoes	Burnett Mary
Zucchini	Burnett Mary, Wet Tropics, Burdekin

Table 14: Estimated number of businesses growing vegetables in the Great Barrier Reef catchment (ABS 2021b)

Commodity	**Burnett Mary**		**Fitzroy**		**Mackay Whitsunday**		**Burdekin**		**Wet Tropics**		**Cape York**		**Total**
	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.	RSE	No.
Beans	19	^	-		-		31	*	-		-		51
Broccoli	11	**	-		-		-		5	**	-		17
Cabbages	7	**	-		-		-		11	**	-		18
Capsicums	11	^	-		-		20	^	5	**	-		37
Carrots	-		-		-		-		5	**	-		5
Cauliflowers	4	**	2	**	-		-		-		-		6
Lettuces	12	**	-		-		-		-		-		12
Melons	38	**	1	*	1		16		8	**	1		65
Mushrooms	2	**	2	**	-		-		-		-		4
Onions	4	**	-		-		-		5	**	-		9
Potatoes	55	*	-		-		3	*	15	**	-		73
Pumpkins	32	*	6	**	2	^	22		32	*	1		96
Sweet corn	12	*	-		-		6		5	**	-		24
Tomatoes	21	^	-		-		15	^	-		-		36
All other vegetables	110	^	6	**	1		39		25	*	1		183
Total	213	^	15	**	2	^	107	^	86	^	1		424

No. Estimate of number of businesses; RSE Relative Standard Error; ^ estimate has a relative standard error of 10% to less than 25%; * estimate has a relative standard error between 25% and 50%; ** estimate has a relative standard error greater than 50%. There are no calculated RSEs for row totals. Within a region the sum of businesses may not equal the total number of businesses as a business may grow more than one vegetable commodity.

Water

Application of water via irrigation is important to maintaining the vegetable industry. The quantity of irrigation water applied to vegetable cropping in GBR catchments in 2019–20 ranged from 1.59 to 4.90 ML/ha (Table 10). The smallest rate of water was applied in the Wet Tropics (1.59 ML/ha) while the largest rate was applied in the Fitzroy (4.9 ML/ha). The average application rate across all regions was 3.03 ML/ha. Differences between regions can be caused by the dominance of different crops in each region, the climatic conditions or the efficiency of the irrigation methods employed. An example of the variability of irrigation requirements between vegetable crops can be seen in the irrigation benchmarks for specific vegetable crops which are 1–2 ML/ha for zucchini, 1.8–2.5 ML/ha for green beans, 2–3 ML/ha for capsicum, 3 ML/ha for sweet potato, 3.4–4 ML/ha for sweet corn, 4 ML/ha for tomato and 3–5 ML/ha for potato (Henderson 2006). Water is obtained from a variety of sources depending on the region, with irrigation schemes providing water to vegetable production in the Wet Tropics, Burdekin and Burnett Mary regions; groundwater is used in the Burdekin, Bowen, Fitzroy and Burnett Mary regions; and on-farm storage is used in the Wet Tropics, Fitzroy and Burnett Mary regions (Henderson 2006).

Agronomic water use efficiency (i.e. tonnes of product produced per ML of applied irrigation water) for vegetable crops in the GBR region can vary greatly. For example, french bean were produced at 2.5 t/ML in Bowen; tomatoes at 10 t/ML in Bowen, Fitzroy, and Burnett Mary; capsicum at 8.3 t/ML in Burdekin and Bowen; sweet potato at 7.6 t/ML in the Wet Tropics and Fitzroy; and potato at 8.7 t/ML in the Wet Tropics (Henderson 2006).

The diversity of crops and regions is also reflected in the irrigation methods used which range from drip irrigation under plastic mulch to travelling guns, travelling booms and centre pivots. Broadly tomato, capsicum and zucchini production mainly use drip irrigation with plastic mulch, while others such as pumpkin and sweet corn use a variety of methods (Henderson 2006).

Limited data was found for water losses, including runoff and deep drainage from vegetable systems in GBR catchments. One study was undertaken in the Burnett Mary and examined spring-summer capsicum and autumn-winter zucchini cropping during a long fallow period between sugarcane cycles (Nachimuthu et al. 2017). Runoff quality and quantity were assessed as well as yields. Approximately 190 mm of runoff occurred from the conventional practice (plastic mulch, bare inter-row and conventional tillage) over 22 runoff events, however it should be noted that during the capsicum crop 190% of the long-term rainfall was received, indicating this period had unseasonably high rainfall which influenced high runoff volumes, while there were no runoff events during the zucchini crop due to low rainfall. Plastic mulch systems concentrate runoff from the bed into the inter-row and can lead to increased runoff (Carey et al. 2015). An improved practice, equivalent to good practice under Hort360 BMP, which had a living mulch in the inter-rows, greatly increased the time to runoff and decreased the overall runoff volume compared to the conventional treatment. Furthermore, deep drainage between the end of the vegetable crop and the start of the following sugarcane crop, although not measured directly, was evident from the movement of nitrate down the soil profile and below the root zone, indicating the potential for deep drainage losses in this system. In a separate capsicum study from the same NRM region deep drainage of 100 mm was observed between transplanting and harvest, although it was unclear from the report how much rainfall and irrigation was received (Stork et al. 2007). Deep drainage losses have also been observed in subsurface drip irrigation practices outside the GBR (Stork et al. 2003). The studies undertaken in the GBR catchment only examine one type of management (i.e. drip irrigation under plastic mulch) in one region, therefore considering the diversity of vegetable types grown, data on water losses is deficient.

Sediment

Only one study was obtained that measured soil loss from vegetable cropping within the GBR catchment. At least 143 kg/ha soil was lost in runoff from conventionally (i.e. plastic mulch and bare inter-rows) cropped capsicum from October to January and a further 26 kg/ha soil was lost during the fallow period between the capsicum harvest and zucchini transplanting, from February to May (Nachimuthu et al. 2017). Since there was no runoff during the zucchini cropping phase there was no soil lost. An improved management treatment, which consisted of a living organic mulch in the inter-rows, equivalent to a good practice under Hort360 BMP, greatly reduced soil loss to 51.8 kg/ha. As reported in the previous section, above average rainfall during the capsicum phase would have increased soil loss and is therefore not representative of the long-term average rainfall conditions although observed differences between management practices would still be relevant. The restricted number of crops and management types examined seriously limit the ability to extrapolate the data broadly to other vegetable crop scenarios.

Nutrients

Fertilisers applied pre or at planting generally occur by application to soil with incorporation by tillage or bed forming, or subsurface band applied. In-crop applications can occur by multiple methods including fertigation (e.g.

sub-surface drip irrigation), surface broadcast, surface applied and incorporated or subsurface band applied, depending on the size and accessibility of the crop. In-crop application via fertigation allows more precise and frequent application of fertilisers to maintain optimum nutritional requirements at the different stages of a crop's lifecycle and when predominately used across a farm is considered good practice under Hort360 BMP.

There is large variability in the quantity of nutrients applied to vegetable crops. Data on actual quantities of nutrients applied to commercial vegetable production in GBR catchments is scarce, however recommended rates for some vegetables are available in guides produced by DAF (Fullelove et al. 1998; Jackson et al. 1997; Loader et al. 1999; Meurant et al. 1999; Wright et al. 2005). For example, sweet corn is recommended to receive 166 kg N/ha, 25 kg P/ha and 162 kg K/ha, split across basal and in-crop side dresses (Wright et al. 2005), while sweet potato is recommended to receive 73 kg N/ha, 40 kg P/ha and 175 kg K/ha, split across basal and in-crop side dresses (Loader et al. 1999). In the guides, leaf, sap and soil testing are recommended to be undertaken to guide fertiliser applications throughout the lifecycle of the crop, in line with good practice under Hort360 BMP, therefore actual applied rates will vary. This is evident in nutrient application rates recorded from 33 capsicum crops in the Bundaberg and Bowen/Gumlu where total applied nutrient rates were 84–224 kg N/ha, 15–141 kg P/ha and 75–406 kg K/ha (Pung 2003). It is also important to remember that in situations where multiple short-term crops are grown in rotation/succession, which is often the case with vegetable crops, actual annual fertiliser rates applied to a field will be the sum of nutrients applied to each crop.

From the literature reviewed it was noted that there was a lack of science-based fertiliser requirements for vegetables in GBR catchments, which has the potential to impact losses if fertiliser is inefficiently applied (Harper and Menzies 2006; Heisswolf et al. 2010). There was also only a limited number of studies in GBR catchments examining the potential for fertiliser loss (Harper 2014; Olsen 1992; Stork et al. 2007), and only one that quantified actual runoff and leaching losses together (Nachimuthu et al. 2017, 2013).

In a study in the Burnett Mary capsicum was grown at five different N rates from 0 to 280 kg N/ha under plastic mulch and subsurface drip irrigation (Olsen 1992). The highest marketable yield was found to occur between 210 and 280 kg N/ha which corresponded to the recommended N rate for the region. However, at this rate 46–91 kg/ha of the applied N was not recovered in the crop biomass and therefore had the potential to be lost from the system via leaching, denitrification and/or runoff. Crop uptake equalled applied N at 140 kg N/ha in this study, reducing the potential for N losses at this rate, however the authors noted there was little incentive for growers to reduce fertiliser application rates as the marketable yield was greatly reduced at lower N rates.

In another vegetable study on sweet corn in the Bowen region after the addition of 250 kg N/ha split across four applications, 80 kg N/ha was not accounted for in crop biomass, resulting in a NUE of 67% (Harper 2014). The nitrogen which was unaccounted for was not in the soil to 1m depth, indicating leaching below 1 m or denitrification losses. The highest nitrate concentrations of leachate samples at the lowest sampled depth of 40 cm was 53 mg/L 48 days after sowing. Phosphorus and K were also applied at 11 kg/ha and 88 kg/ha, respectively, however in contrast to the underutilisation of nitrogen, the use efficiency of P and K was positive. Phosphorus and potassium had a use efficiency of 370 and 240% respectively, indicating no potential losses of these applied nutrients.

In a study in the Burnett Mary region potential losses of N were calculated for single row capsicum, single row zucchini, double row capsicum and double row sweet corn grown in rotation over two years (Stork et al. 2007). Unaccounted for nitrogen (taking into account soil mineral N at planting and harvest, applied fertiliser and crop N uptake) for each crop equated to 142, 105, 133 and 42 kg N/ha respectively, which could have been lost via deep drainage, runoff or denitrification.

In the same study that measured runoff volumes and soil loss in a capsicum and zucchini rotation, nutrient losses in the runoff were also quantified (Nachimuthu et al. 2017). Over the two crop rotations grown under conventional practices (plastic mulch, bare inter-row and conventional tillage), including a fallow, total N, DIN and DON losses equated to 3.5, 0.7 and 1.1 kg/ha, respectively (extracted from graphed data). Total P and FRP lost in runoff equated to 1.3 and 0.6 kg/ha, respectively (extracted from graphed data). The improved practice, with living mulch inter-rows and reduced fertiliser rates, equivalent to best practice, greatly reduced all measured nutrient losses by >50% compared to the conventional practice. These values are likely to be under-estimations of true losses, as runoff volumes were occasionally too large to measure accurately. However, leaching losses between capsicum harvest and zucchini harvest under conventional practices were estimated at 100–110 kg N/ha, using soil mineral N profiles (Nachimuthu et al. 2013), which is significantly higher than losses via runoff. Rainfall during the fallow period and frequent irrigation during the zucchini crop likely moved nitrate beneath the crop root zone enabling leaching. Plastic mulch maintains a shallow moist zone which negates the need for crops to establish deep roots, therefore increasing the possibility of N leaching beneath the root zone if irrigation is not optimised (Heisswolf et al. 2010). This highlights the importance of optimising irrigation to suit crop demands.

It is clear from the available literature specific to GBR catchments that nitrogen inputs often do not match nitrogen crop uptake, creating the potential for losses. However, the distinct lack of studies which quantify these loss pathways leaves a significant amount of uncertainty about actual losses to water bodies. The large variety of vegetables grown in the GBR catchments and the different management methods employed in different climatic/soil conditions complicates attempts to quantify representative losses for the industry as a whole.

Pesticides

Due to the large number of vegetable types and therefore potential pests, there are considerable pesticides registered for use in the vegetable industry. Hort Innovation maintains agrichemical regulatory risk assessments for 27 vegetables types, which includes information on pest and approved active chemical constituents to combat pests, as well as the risk to maintaining access and use of the chemical for the stated purpose, considering regulatory restrictions on chemical use in overseas jurisdictions. In addition to this an online database, Infopest, maintained by Growcom, provides access to data on all chemicals approved for use by APVMA in Australia. No quantitative data on chemicals applied was found.

No studies were found that measured pesticide losses during vegetable crops in GBR catchments. The lack of data on the quantity of chemicals applied in vegetable cropping, coupled with the lack of measured pesticide losses and limited runoff data from vegetable cropping reveal a large gap in knowledge concerning pesticide impacts on water bodies in GBR catchments.

Pineapples

Pineapples are grown in more than 80 countries of tropical and subtropical regions. Oceania (including Australia) comprises only 0.03% of the global area harvested for pineapples, although the region is, alongside America, the highest yielding worldwide (Reinhardt et al. 2019). In Australia, most pineapple production occurs in Queensland, with major production areas in South-East Queensland, Wide Bay, Yeppoon, Rollingstone and Mareeba. For the year ending June 2020, the Australian pineapple industry produced 66,069 t (valued at $52.2 m), with 36% sent to be processed (Hort Innovation 2020).

The GBR region has around 2,034–2,385 ha under pineapple production, mostly within the Burnett Mary and Fitzroy regions, although smaller areas within the Burdekin and Wet Tropics regions are also reported (Table 6; Appendix 1). It was estimated in 2019–20 that the Burnett Mary, Fitzroy and Wet Tropics had 24, 17 and 10 growers respectively (Table 12). Land requirements for growing pineapple under optimal conditions as noted as: free-draining soils to at least 1m depth and pH between 4.5 and 5.6, optimum temperature of 32°C (day) and 20°C (night), rainfall of 750 mm distributed well throughout the year, slopes of 2–6 percent, NE aspect (DAF 2013). Pineapples are generally planted on raised beds to encourage drainage and prevent *Phytophthora* root rot (Ciesiolka et al. 1995). Multiple crops are harvested from the one crop over 3–4 years, followed by a period of fallow (e.g. 3–6 months) when the soil is left bare. During this time the soil is managed with cultivation and/or herbicides to control weeds and prevent resprouting (Coughlan and Rose 1997).

The Pineapple Strategic Investment Plan 2017–21 (Hort Innovation 2017) notes that 'there is an appreciation of the need to adopt best management practice (BMP) approaches and to develop and adopt integrated pest and disease management (IPDM) practices… many in the industry have adopted BMP approaches and acknowledge the compliance required through adopting farming practices that conform to the regulatory protection of the Great Barrier Reef.' Information regarding BMPs is collated through the Pineapple Best Practice Management Manual (2009), accessible by Industry Log-in on Australian Pineapples <https://australianpineapples.com.au/members/>. Reviews on aspects of global pineapple production have been published by Sanewski et al. (2018), with an Australian industry snapshot provided by Reinhardt et al. (2019). Growcom represents the biosecurity interests of Australian pineapple producers as members of Plant Health Australia and signatories to the Emergency Plant Pest Response Deed (Plant Health Australia 2021). Queensland Department of Agriculture and Fisheries website provides information including research and development, archived publications, pest and diseases, harvesting and marketing and varieties, plus frequently asked questions pages regarding planting, nutrition, fertilising and irrigation (including login to environmental management system) of pineapples in Queensland (DAF 2014). The Soil Conservation Guidelines for Queensland include a chapter on soil conservation in horticulture which refers to pineapples explicitly in relation to managing runoff with site planning, drains and inter-row groundcovers (Carey et al. 2015). The Queensland Government's Reef Water Quality Program also funds Hort360 BMP, which is delivered by Growcom and includes workshops and training for pineapple growers, with targeted modules and specific focus areas including environmental stewardship, industry best practice standards in Reef catchments within a Reef certification framework (Growcom 2020). Pineapples are specifically mentioned in the Hort360 Reef Certification Management Practices with respect to management of groundcover on the bed and inter-row for sediment control (Growcom 2021).

Water

Unlike other irrigated crops, such as vegetables and bananas, pineapples are not heavily or frequently irrigated, as the plant is able to store water and excessive water can have detrimental effects (e.g. root diseases). Irrigation use is higher in the Burdekin and Wet Tropics than in the Burnett Mary. The Pineapple Best Practice Manual states irrigation may occur directly after planting, during dry springs, prior to flower initiation and during droughts (Newett et al. 2006). Irrigation predominately occurs via overhead irrigation; the use of drip irrigation has also been investigated but setup can be cost prohibitive.

Limited data on runoff and deep drainage losses from pineapple plantations in the GBR catchment are available. Land requirements suggest that the generally sandy free-draining soil used to grow pineapples would be prone to deep drainage losses, however published measured data was not found. Confirmation is needed to confirm whether recently established pineapple demonstration sites include observations of N leaching below the root zone. Research to date has mainly focussed on sediment losses from runoff, therefore water losses via runoff were also quantified. Annual runoff from a pineapple trial at Imbil in the Burnett Mary on steep slopes (33–38%) recorded runoff of 42–59% of rainfall during above average rainfall conditions and 16–30% during average and below average rainfall conditions (Ciesiolka et al. 1995). In comparison from a site near Goomboorian in the Burnett Mary averaged over three years on gentler furrow slopes (<6%) than Imbil, 20% (213 mm) of rainfall was lost as runoff from a conventionally managed pineapple crop. Bare soil at the same site lost 27% (286 mm) of rainfall as runoff, while an improved practice which includes pineapple residues in the inter-row reduced runoff losses to 14% (150 mm) of rainfall (Coughlan and Rose 1997).

No data was found on losses from actively irrigated pineapples. This could reflect the cropping conditions at the time of data collection which were mostly ~30 years ago or the limited use of irrigation was not recorded in the studies.

Sediment

Soils under pineapple management are very susceptible to soil and suspended sediment losses, therefore erosion has been the primary focus of research. The Pineapple Best Practice Manual includes a chapter devoted to ‘management of erosion and sedimentation’, which highlights practical measures which can be implemented to reduce erosion and soil loss. These include but are not limited to: buffer zones, sediment ponds, grassed filter strips, tied ridges, diversion channels, mulching, erosion control matting and cover crops (Newett et al. 2006).

Management practices that reduce soil loss have been trialled at locations within the GBR catchment and just outside the southern end of the catchment in the South East Queensland region. At a site near Imbil in the Burnett Mary different row lengths were trialled, positioned up-and-down the slopes which were 33–38% (Ciesiolka et al. 1995). In the plant crop 178 t/ha of soil was lost from the longest row (22 m) while 65 and 76 t/ha were lost from the 7 and 12 m rows. Soil loss increased with slope length in another trial at the same site (Palis et al. 1997). Soil loss was highest during the plant crop and significantly reduced by between 58–93% in the subsequent two years. Average annual sediment concentrations were 3000–6400 mg/L for the 7 and 12 m rows, and between 24700 and 4400 mg/L for the 22 m row. During the plant crop the canopy is still developing so the soil is exposed to rain impact directly, resulting in increased sediment losses compared to later years when the crop canopy is well developed. These findings were further supported by a trial near Goomboorian in the Burnett Mary, where soil loss of 127 t/ha was recorded from the conventional practice during the first year, and then 21 and 4 t/ha soil loss in the second and third year, respectively (Coughlan and Rose 1997). Sediment concentration reduced from 91 kg/m^3 in the plant crop to 1.3 kg/m^3 in the third year. At Goomboorian rows ran across the slope so furrow slopes were <6%. At the Imbil site the contribution of the suspended sediments to the total soil load (i.e. bed load plus suspended load) was found to increase over the crop cycle. In the first year only 10% of the soil loss was suspended sediment while after five years ~100% of the soil loss was from the suspended load, however this was because the bedload was decreasing, and the suspended sediment load was relatively stable (Coughlan and Rose 1997).

More recent trials have investigated the use of mulch covers in the inter-row to reduce soil losses including placing whole pineapple plants in inter-rows at different spacings and sugarcane mulch (Abel 2021). These practices are highlighted in the Soil Conservation Guidelines for Queensland to slow water movement and trap soil in pineapple plantations (Carey et al. 2015). Placing whole plants in the inter-row reduced soil loss from 50.6 t/ha to 2.9–16.9 t/ha depending on spacings while sugarcane mulch eliminated soil loss completely. At another site placing whole pineapple plants along an entire row reduced soil loss from 80.7 to 5.7t /ha, while only placing pineapple plants in the inter-row at the end of the row reduced losses to 15.4 t/ha (Abel 2021).

Nutrients

Pineapples require significant nutrient inputs to ensure a quality yield, with the plant crop requiring more nutrients than the ratoon crops. The Pineapple Best Practice Manual provides a guide of typical nutrient requirements

(Newett et al. 2006). It states pre-plant applications of 120 kg N/ha, 50–100 kg P/ha and 300 kg K/ha are required, which are generally applied in granular form and incorporated into the soil. The plant crop requires in-crop applications of 450–480 kg N/ha, up to 25 kg P/ha and 475–535 kg K/ha. These can be applied as granular side dresses or foliar applications. Side dressing allows more nutrients to be applied in one application compared to foliar applications, which reduces labour requirements, but increases the risk of losses. In comparison frequent smaller applications requires more labour but decreases the risk of large off farm losses. During the ratoon crop 300–340 kg N/ha, up to 25 kg P/ha and 160–280 kg K/ha are required and are applied using the same methods as the plant crop. In total one cycle's (preplant + plant crop + ratoon crop) fertiliser requirements can be 870–940 kg N/ha, 50–100 kg P/ha and 935–1,120 kg K/ha. The Pineapple Best Practice Manual also states that leaf sample tests should guide the application of additional nutrients and take into account pre-existing soil nutrients (Newett et al. 2006). The potential to reduce pre-plant urea applications was recently investigated on a farm in the Burnett Mary and found that reductions in pre-plant fertilisers did not impact productivity (Griffin 2020a). Although not measured in the trial, lower rates of N application have the potential to reduce the risk of offsite movement of N. Furthermore, the potential to utilise enhanced efficiency fertilisers, such as controlled release fertilisers, instead of granular urea has recently gained interest to better match crop N demand to maintain yields with the additional benefit of also possibly reducing off farm losses, however data on these trials is currently not publicly available.

Data on nutrient losses via runoff or deep drainage from pineapple plantations are limited in the GBR catchment. However, due to the significant amounts of N applied and the sandy free draining soils, N losses via leaching are a concern. At two separate sites with differing fertiliser inputs, slopes and soils, 36 and 49% of N inputs (including preplant fertilisers, side-dress fertilisers, foliar fertilisers and existing plant and trash material) were lost as leachate below the root zone, which was equivalent to 274 and 622 kg N/ha, respectively (Abel 2020). At the Goomboorium site a series of leachate samples taken at 1 m depth after a rainfall event also suggested high levels of nitrate losses from deep drainage with the highest nitrate concentration in leachate of ~30 mg/L (Coughlan and Rose 1997). This indicates that indeed significant leaching of N can occur in pineapple cropping, depending on N inputs (e.g. rate, type, timing and application method) rainfall and soil conditions.

At Goomboorium an assessment of nutrient losses determined that the majority of N and K was lost from the system in the soluble form. This was also reported from another pineapple site where it was estimated 30–50% of individual nutrient applications were lost in runoff (Ciesiolka et al. n.d.). However, these results were formed using electrical conductivity measurements and not actual measurements of N, P and K (Ciesiolka et al. n.d.). The conventional treatment at Goomboorium after receiving 303 kg N/ha in addition to 114kg N/ha from existing plant biomass residues lost, via runoff, 30 kg N/ha associated with soil and 83 kg N/ha in the soluble form. Harvested fruit accounted for 37 kg N/ha, 4 kg P/ha and 97 kg K/ha. Even after accounting for losses via runoff, this partial nutrient budget suggests a surplus balance of the three main nutrients indicating that there was the potential for large losses from other sources such as leaching (Coughlan and Rose 1997).

A bio-reactor was trialled on a pineapple plantation in the Burnett Mary to reduce nitrate concentrations in leachate moving off farm. The bio-reactor provides conditions conducive to the reduction of nitrate to nitrous oxide and dinitrogen gas, therefore reducing the amount of nitrate in groundwater leaving the farm. Preliminary results show a reduction in water nitrate concentrations leaving the bioreactor and moving off farm of 45.8%, compared to water entering the bio-reactor from the farm (Griffin 2020b). Reducing nutrients in runoff before they move offsite was also trialled with the use of a sediment pond, which collected the first flush of runoff after rainfall (Australian Pineapples 2019a). Nutrient concentrations in the runoff sediment and runoff water collected in the pond reduced over five months. The N concentration in collected water decreased by 93% while N in sediment was consistently low. The P concentration in water and sediment was reduced by 93 and 46%, respectively. The exact methods which occurred to reduce N and P concentrations in the pond were not determined.

Pesticides

Since pineapple production is generally a monoculture with a short fallow period between crop cycles the build-up of pests and diseases can occur requiring the use of pesticides. The strategic agrichemical review process identified root and heart rot (*Phytophthora cinnamomi* & *P. nicotianae*) as high priority diseases in pineapples (Hort Innovation, 2019). Insect and mite pests identified as high priority were Root knot nematode and Root lesion nematode (*Meloidogyne* spp. and *Pratylenchus* spp.), Pineapple flat (red) mite (*Dolichotetranychus floridanus*), Symphylids (*Scutigerella* spp, *Hanseniella* spp.), Pineapple mealybugs (*Pseudococcus* spp. & *Dysmicoccus brevipes*) and white grubs (*Scarabaeidae*).Weeds identified as high priority were Blue billygoat weed (*Ageratum houstonianum*), Billy goat weed (*Ageratum conyzoides*), Praxelis (*Praxelis clematidea*) and Pigweed (*Portulaca oleracea*). As of 2019 the review process reported 16 products were available for disease control in pineapples, 22 products for the control of insects, mites and other pests, 11 products for weed control and 10 chemical permits were current for use in pineapples. Growth regulators are also an important aspect of pineapple production as they are used to induce flowering.

Reducing the use of pesticides and increasing the efficacy of pesticides, which would both decrease potential losses offsite, have been or are currently being investigated in studies funded by industry and government (Australian Pineapples 2020, 2019b). However offsite losses are either not being measured as part of the project or are currently unpublished.

The measurement and publication of pesticide losses from pineapple production in the GBR catchment is very limited. Measurements of diuron and bromacil occurred in conjunction with the implementation of a sediment pond to reduce offsite movement of pollutants (Australian Pineapples 2019a). Initial concentrations of diuron and bromacil after the first flush associated with rainfall was 40 and 15 mg/kg in water, respectively. Concentrations of diuron and bromacil in ponded water reduced by 95 and 83% over five months of monitoring, respectively. Initial pesticide concentrations in sediment were 1.1 and 0.11 mg/kg for diuron and bromacil, respectively. After five months for diuron and bromacil concentrations reduced by 78 and 18%, respectively. Information on the pesticide applications rates and timing were not publicly available for this study.

Other

Commodities in the ‘production of irrigated agriculture and plantation’ ALUM class not considered in this review include but are not limited to berries (e.g. strawberries, blueberries), passionfruit, grapes, turf and rice. Other commodities which are predominately dryland have not been considered in the irrigated class.

Knowledge gaps identified

This report conducted a knowledge gaps rapid assessment in the form of a qualitative synthesis. A quantitative synthesis was out of scope of this report and would not have been able to be undertaken due to the highly variable and in some cases, limited, datasets available for comparative analyses. Available spatial data was initially used to inform the aggregation of information into commodity classes by determining the distribution and extent of commodity classes in the GBR catchment. However spatial data is not considered explicitly in this synthesis, as this report assembles available knowledge based upon water quality search query parameters (i.e. sediments, nutrients and pesticides) in GBR catchments and in-scope commodity classes, identified as: cereals and pulses, cotton, bananas, vegetables, macadamias, avocados, vegetables and pineapples. We acknowledge that this review complements projects underway elsewhere (e.g. examination of next-generation land suitability data and support tools) and forms a component of a wider synthesis process that combines spatially referenced and quantitative site data together.

While management practices have been considered within the Reef certification framework e.g. Hort360, further knowledge is required to quantify commodity-specific activities to prioritise efforts to improve water quality parameters in the GBR catchment. Table 15 summarises current knowledge gaps in each commodity across the four water quality parameters used in this report and Appendix 2 outlines all study sites for each commodity in the GBR catchment. Some gaps are common across multiple commodities (e.g. limited measured data, applied fertiliser rates, applied pesticide rates) while other gaps are specific to individual commodities (e.g. accounting for recirculated losses in cotton, contribution of soil mineralisation to losses in cereals, unique plastic mulch system in vegetables).

Current data on the fertiliser rates applied were not readily available across most commodities using the search criteria applied in the rapid assessment approach. Without up-to-date knowledge on rates applied in the GBR catchment, assessments of potential losses and loss pathways cannot be broadly made with confidence. Surveying growers can provide baseline data, as reported for some commodity types. For example, the Cotton Research Development Corporation surveys growers across Australia and provides a regional breakdown of that information in published reports. In the case of cereals and pulses the Grains Research Development Corporation conducts a farm practices survey. However, although there are questions concerning fertiliser application and management decisions relating to fertiliser use, there are no questions on the rate of applied fertiliser. Systematic aggregation of this information through a stakeholder engagement workshop will be critical to confirm best-available information for each commodity type, and to what extent the FAIR (Findable, Accessible, Interoperable, Reusable) principles (Australian Research Data Commons, 2021) can be applied when assembling and managing the data.

Data on pesticide rates and pesticides was also limited across most commodities using the search criteria applied. The only commodity found to routinely survey and collect data on pesticide usage was cotton, with surveys reporting collected data on cotton region, pesticide type, rate and area applied. Data on pesticide rates and types used may be collected by other industry or NRM bodies in the GBR region as part of BMP programs, but further stakeholder engagement to clarify information sources not captured through the search approach applied in this project is required. Pesticide usage data would provide a basis for assessing whether the use of pesticides in a commodity warrants further investigation, while also providing a baseline dataset to gauge any future reductions or increases in pesticide usage.

The quantity of data available on measured water, sediment, nutrient and pesticide losses was generally deficient across most commodity types, with bananas having the most available data. Avocados had the least data of the commodities assessed, with no study sites representing monitored loss data in the GBR catchment found using the search criteria. Similarly, macadamias only had one study site with measured loss data, therefore indicating that data on tree crops is deficient. There were two study sites that collected loss data from vegetables in GBR catchments, however they both occurred in the Burnett Mary, with no information found for the larger area cropped to vegetables in the Burdekin, indicating data on losses from vegetables is deficient. There were three pineapple study sites in the Burnett Mary that monitored some water quality impacts, but no sites in the Fitzroy which had the second largest area cropped to pineapples. More recent studies examining management interventions in pineapple plantations are ongoing but little information is yet publicly available. Cotton had four study sites that were all focussed on the main growing region of the Fitzroy. Cereals and pulses had five study sites and temporal data collection equivalent to ~71 years (not including rain simulator and pure modelling studies). There were an additional four rainfall simulator studies that, under short-term experimental conditions, assessed management effects and mechanisms causing losses. Data from cereals and pulses benefit from the use of longer-term studies (e.g. Gordonstone and Brigalow Research Stations), making the data the most temporally exhaustive of those assessed. Bananas had the most data on measured losses, which were representative of the main growing region of the Wet Tropics. There were ten banana study sites and temporal data collection equivalent to ~24 years (not including rain simulator and pure modelling studies).

Commodity specific assessments are summarised as:

Cereals and pulses

Knowledge of offsite losses in cereal and pulse cropping primarily focussed on the basaltic clays of the Fitzroy (Appendix 2; Table 15), which is the main cereal and pulse growing region in the GBR catchment. The knowledge base has benefited from the use of longer-term studies (i.e. >5 years) that monitor loss components (i.e. water, sediment, nutrients and pesticides), enabling better temporal representation of losses (Appendix 2; Carrol et al. 1997; Rogusz 2019; Thornton et al 2007). These datasets highlight the rainfall driven nature of losses and consequently the highly variable year-to-year losses (Rogusz 2019). Management actions to mitigate losses appear understood and include zero tillage (Sallaway et al. 1988), contour banks (Murphy et al. 2013) and maintaining high ground cover during the wet season (Hulugalle et al. 2002; Carroll et al. 1997; Rhode and Yule 1995). However further knowledge is required concerning the underlying causes of N losses from these low N input systems and how mineralisation of soil and residue N contribute to losses. A knowledge of what quantity of nutrients are applied to cereals and pulses in GBR regions is also required. Although sediment losses to waterways are apparent in the datasets (Murphy et al. 2013; Rogusz 2019; Elledge and Thornton 2017) the level of bioavailable nutrients that may become available offsite in these highly mobile fine basaltic clays has yet to be determined for cereal and pulse cropping.

Irrigated cotton

Knowledge of offsite losses in cotton have focussed on the main growing region located in the Fitzroy, so spatial representation across regions is not of concern. However, if the cotton industry expanded further north as has been proposed (into the Burdekin and above), then further monitoring of losses in these areas would be needed. There are limited (four; Appendix 2; Table 15) study sites in the region and considering the large inputs of irrigation water and the fact irrigation water impacts directly on pollutant losses, only one study looked at the effect of differing irrigation methods on losses (McHugh et al. 2008). The studies reported generally described losses from the paddock to tail drains, however cotton cropping is unique in that the recirculation of irrigation water around farms is widespread. Therefore, it cannot be assumed that all losses from the paddock to the tail drain are automatically lost off farm. Although methods to minimise paddock losses are valid and would have flow on effects in reducing losses to irrigation infrastructure and waterways, the values obtained may not be representative of true losses to waterways. Studies that attempted to measure losses off farm and downstream of cotton did report elevated TN and TP concentrations (Noble et al. 1996) and pesticide losses (Simpson et al. 1998) under high rainfall conditions. This indicates potential impacts to water quality are present and in situations where the capacity of irrigation infrastructure to contain water is exceeded (i.e. large rain events) losses will occur, but further quantification is required. Furthermore, all studies were over 20 years old and occurred before or during widespread adoption of BMP, hence reported losses may not be representative of current practices.

Bananas

Data on losses from bananas, although more advanced than other in-scope commodities, is still lacking. Considering that fertiliser rates have historically been large and combined water inputs from rainfall and supplementary irrigation are also large nutrient losses are expected. Indeed, studies in the Wet Tropics indicate nutrient losses via deep drainage (Armour et al. 2013; Rasiah and Armour 2001) and runoff (Masters et al. 2017) can be large. Similarly, large sediment losses both as bedload (McKergow et al. 2004) and TSS (Faithful and Finlayson 2005; Masters et al. 2017), have been recorded. However, small nutrient losses via deep drainage have also been recorded when nutrients are applied efficiently (Masters et al. 2017) demonstrating the potential for variability in losses and the potential for mitigation. Regulations regarding fertiliser rates, fertiliser application area and inter-row ground cover percentage aim to constrain nutrient and sediment losses, however, losses under these new conditions need to be investigated, for example through quantification at field trials across a variety of sites. Confirmation from industry is required on whether the latest survey on N fertiliser application rate is the one undertaken by Sing (2012). Measured losses to date have in some instances used fertiliser rates higher than that regulated (Armour et al. 2013), which will impact measured losses. Although losses of pesticides from plantations have been reported (Masters et al. 2015), they are considered less critical compared to nutrient and sediment losses due to the quantities applied and frequency used, consequently they are less studied than nutrients or sediments.

Macadamias

Macadamias are mostly grown in regions with rainfall exceeding >~1,000mm per year. The recommended annual N and P fertiliser application rates are approximately 30–80 kg N/ha and 2.5–7.5 kg P/ha, respectively, though there is a lack of data on the amounts of fertiliser N and P actually used in the macadamia industry. Macadamia orchards are irrigated generally with water-efficient techniques such as sprinklers or drippers, which pose little risk of direct runoff and leaching. However, severe runoff and soil erosion can occur during intense rainfall events, particularly in orchards on slopes and/or with bare inter-row areas. Ground cover with shade-tolerant grasses in the inter-row area should help minimise runoff losses. Only one study in the Burnett Mary region (Stork et al. 2009) was found, which recorded 0.177 ML/ha year for surface runoff, 5.7 kg/ha/year for sediment loss, 0.28 kg N/ha/year for total N loss from surface flow, and 0.35 kg/ha/year for total P loss, with no pesticides and their metabolites detectable in the sediment and runoff samples. Data are absent for the other main growing regions (Fitzroy, Mackay Whitsunday and Wet Tropics).

Avocados

The avocado-growing regions in the GBR catchment mostly have an average annual rainfall of >900 mm. Thus, lateral and vertical losses of water and sediments can occur in high rainfall events, particularly for farms on slopes and/or with bare inter-rows. Growers use approximately 69–528 kg N/ha/year (mean 212 kg N/ha/year) and 0–100 kg P/ha/year (31 kg P/ha/year on average), often much higher than the recommended rates (110 kg N/ha/year) given in the Best Practice Resource. Although efficient management techniques such as fertigation and the ‘little and often’ approach for N application are commonly adopted in the industry, nutrient losses along with rainwater and sediment runoff in high rainfall events remain highly likely, particularly on farms where excessive fertiliser N is applied. As avocado trees are generally grown on well drained soils, N loss through leaching is also possible. Nonetheless, no measurements of any pollutant loss from avocado orchards in the GBR regions were found using the search criteria applied.

Vegetables

Knowledge of losses from vegetable cropping in GBR catchments is very deficient. Only two studies were found from the Burnett Mary indicating the data is not spatially or temporally representative (Appendix 2; Table 15). The vegetable class is unique in that it contains many individual vegetable types with differing nutrient requirements, management methods and irrigation requirements. However, studies only examined one type of management (i.e. drip irrigation under plastic mulch). The studies reported losses of sediment and nutrients through runoff and the potential for deep drainage losses (Stork et al. 2007; Nachimuthu et al. 2017), although there was no data on pesticide losses. The potential for nutrient losses is high due to the large fertiliser inputs required to grow vegetables, although it is also evident that this loss may be minimised by management activity such as efficient application of fertigation in drip irrigation systems. Currently an assessment of the amount of nutrients applied to vegetables cannot be made due to the lack of data on applied fertiliser rates for all vegetables. Calculating annual nutrient rates for a paddock is often complicated by the sowing of multiple crops, with different nutrient inputs, each year. Results from the search suggest that methods to calculate nutrient requirements of vegetables are lacking, creating the potential for fertiliser to be applied at rates, exceeding plant requirements and exacerbating losses.

Pineapples

Data on pollutant losses from pineapple plantations in the GBR catchment is deficient. Only three study sites that measured pollutant losses were found in the Burnett Mary, which is the main growing region in the GBR catchment, and there were no studies in other growing regions (Appendix 2; Table 15). Early studies on losses from pineapple plantations focussed primarily on quantifying and managing the large erosion and sediment losses from pineapples caused by the lack of groundcover during the fallow and early crop growth (Ciesiolka et al. 1995; Coughlan and Rose 1997). However, the highly permeable soils used to grow pineapples coupled with the high rates of nutrients applied make the off-site movement of N via deep drainage also of concern. Indeed, the limited available data supported this assertion by reporting high losses of N in leachate (Abel 2020; Coughlan and Rose 1997). There was no data on the annual losses of pesticides or the percentage of applied pesticides lost in runoff or deep drainage. More information is required to assess whether current demonstration sites located in the GBR catchment measure water quality impacts.

Table 15: Knowledge gaps in water quality impacts from in-scope commodities in the Great Barrier Reef catchment

Commodity	General observations	Water	Sediment	Nutrients	Pesticides	Datasets*
Cereals and pulses	• There is good evidence of the rates of pollutant losses from longer term trials in the Fitzroy but limited studies in the Burdekin. • Low applied nutrient rates contrast with other commodities, and the effects of future nutrient rate increases should be considered. • Considering low nutrient inputs, the contribution of N in residues and soil mineralisation to relatively high measured N losses has not been investigated.	• Limited data on water losses through runoff and deep drainage in the Burdekin and deep drainage in the Fitzroy.	• Limited data on sediment losses in the Burdekin.	• Limited data on nutrient losses (N and P) in the Burdekin. • Contribution of residues to nutrient losses in runoff (including N fixed from atmosphere and stored in pulses) not measured. • Contribution of soil N mineralisation to N losses are not measured. • The effects of possible future increased nutrient rates on potential losses not understood. • Requires better understanding of the contribution of bioavailable nutrients from cropped Vertosols to water bodies. • Applied nutrient rates in GBR catchments not documented and accessible.	• Limited data on pesticide losses in the Burdekin.	• Seven studies in Fitzroy and one each in Wet Tropics and Burdekin.

Commodity	General observations	Water	Sediment	Nutrients	Pesticides	Datasets*
Irrigated cotton	• Cotton, unlike most other crops, has widespread use of recirculated farm water, which to date has not been accounted for when determining actual losses from paddock to waterway. • Data is generally deficient or outdated across pollutants to match current BMP.	• Limited data on water loss through runoff and deep drainage in Fitzroy that represent losses from farm to water bodies.	• Limited data on sediment loss through runoff in Fitzroy that represent losses from farm to water bodies. • Sediment losses are not measured from current BMP.	• Limited data on nutrient (N and P) loss through runoff in Fitzroy that represent losses from farm to water bodies. • Nutrient losses are not measured from current BMP. • Nutrient losses are not reported as current fractions used for GBR reporting (e.g. DIN, PP etc).	• Limited data on pesticide loss through runoff in Fitzroy that represent losses from farm to natural water bodies. • Most measured loss data is based on outdated pesticide use, not currently used pesticides and rates. • Applied pesticide rates in GBR are not documented and easily accessible.	• Five studies in Fitzroy.
Bananas	• Data is generally outdated across pollutants to match current BMP and regulations.	• Limited temporally representative measurements of water losses from runoff and particularly deep drainage, in relation to variable annual water inputs.	• Limited temporally representative measurements of sediments in relation to variable annual water inputs. • Limited data on sediment losses from current BMP.	• Limited temporally representative measurements of nutrient losses from runoff and particularly deep drainage, in relation to variable annual water inputs. • Measurements are not based on current BMP and regulated rates. • Nutrient losses are not reported as current fractions used for GBR reporting (e.g. DIN, PP etc).	• Limited data on pesticides losses via runoff and deep drainage in Wet Tropics • Applied pesticide rates in GBR catchments not documented and accessible.	• Nine studies in Wet Tropics and one in Burnett Mary.

Commodity	General observations	Water	Sediment	Nutrients	Pesticides	Datasets*
Macadamias	• Data on pollutant losses are lacking or absent in all regions, especially in Burnett Mary and Fitzroy which host 95 and 3.4%, respectively, of all orchards in the GBR catchment. • Common use of efficient irrigation techniques (sprinkler & drip) and N fertiliser application methods (fertigation, 'little and often') may mitigate loss risks. • Confirmation required of limited measurements that demonstrated great risks of sediment and N loss, moderate risk of dissolved P loss and very low risk of pesticides loss.	• Limited data on water loss through runoff and deep drainage in Burnett Mary and Fitzroy.	• Limited data on sediment losses via runoff in Burnett Mary and Fitzroy.	• Limited data on N and P losses via runoff and deep drainage in Burnett Mary and Fitzroy. • Applied rates of N and P fertiliser in GBR catchments not documented and accessible.	• Reported very low risk of pesticide loss requires confirmation through measurements at multiple sites. • Applied pesticide rates in GBR catchments not documented and accessible.	• One study in Burnett Mary.
Avocados	• Absence of data on pollutant losses in all GBR regions. • Measurements required, especially in Burnett Mary and Wet Tropics, which account for 60 and 38%, respectively, of all avocado farms in the GBR catchment. • Common use of efficient irrigation and N fertiliser application techniques may mitigate loss risks, but. excessive N use may be widespread, posing great risks of N loss in high rainfall events.	• No data on water loss through runoff and deep drainage in Burnett Mary and the Wet Tropics.	• No data on sediment losses via runoff in Burnett Mary and the Wet Tropics.	• No data on N and P losses via runoff and deep drainage in Burnett Mary and the Wet Tropics. • Applied rates of P fertiliser in GBR catchments not documented and accessible.	• No data on pesticides losses via runoff in Burnett Mary and the Wet Tropics. • Applied pesticide rates in GBR catchments not documented and accessible.	• Nil.

Commodity	General observations	Water	Sediment	Nutrients	Pesticides	Datasets*
Vegetables	• Large variety of vegetable crops and management types coupled with deficient GBR specific data indicates a large knowledge gap. • Current actual rates of applied fertiliser and pesticides not available to form a baseline. • Vegetables grown under plastic mulch are unlike other systems already studied in GBR catchments and importing knowledge from other crops to model outputs may prove difficult without in-situ GBR specific measurements.	• Limited data on water loss through runoff and deep drainage in Burnett Mary and Burdekin.	• Limited data on sediment losses in Burnett Mary and Burdekin.	• Limited data on nutrient (N and P) losses in Burnett Mary and Burdekin. • Applied rates of N and P fertiliser in GBR catchments not documented and accessible. • Optimisation of fertiliser rates and methods to better match nutrients to crop requirements.	• Limited data on pesticide losses in Burnett Mary and Burdekin. • Applied pesticide rates in GBR catchments not documented and accessible.	• Two studies in Burnett Mary.
Pineapples	• Existing evidence suggests the potential for large losses of sediments and nutrients from pineapple production, particularly via deep drainage. • Irregular use of irrigation, with limited data on pollutant losses directly associated with irrigation. • Full details of results from recent studies are not yet published.	• Limited data on water losses through runoff and deep drainage in the Burnett Mary and Fitzroy. • No quantification of the proportion of losses associated with irrigation.	• Limited data on sediment losses in the Burnett Mary and Fitzroy. • No quantification of the proportion of losses associated with irrigation.	• Limited data on nutrient losses (N and P) in the Burnett Mary and Fitzroy. • No quantification of the proportion of losses associated with irrigation • Nutrient losses are not reported as current fractions used for GBR reporting (e.g. DIN, PP etc).	• Limited data on pesticide losses in the Burnett Mary and Fitzroy. • No quantification of the proportion of losses associated with irrigation.	• Three studies in Burnett Mary.

Commodity	General observations	Water	Sediment	Nutrients	Pesticides	Datasets*
	• More measurements on pollutant losses are required in the Burnett Mary and Fitzroy.					

*Data outlined in Appendix 2 - Study sites with reported water quality impacts measured under field or experimental conditions, according to commodity type and Natural Resource Management region in the Great Barrier Reef catchment.

Conclusions and recommendations

Here, we report on the findings from a rapid assessment, qualitative synthesis approach to curate information relating to losses of water, sediments, nutrients and pesticides from specified horticulture and cropping production in Great Barrier Reef catchments. From this work we identified knowledge gaps relating to paddock and offsite losses of water, nutrient, sediment and pesticides for a number of commodities grown in GBR catchments (as summarised in Table 15).

The work undertaken here may be used to inform the design and implementation of on-ground actions within GBR catchment regions, as well as assist with program and policy decisions; anticipated climate change scenarios and impact for horticulture and cropping requires further consideration in this context. We also acknowledge the inter-dependency of this activity alongside other concurrent projects, for example projects relating to soils and land suitability data, tools and frameworks. Further work to relate these is recommended.

Commodities determined to be in scope for this review were cereals and pulses, bananas, cotton, macadamias, avocados, vegetables and pineapples.

Information on losses of water, sediments, nutrients and pesticides from specified cropping and horticulture in GBR catchments, based on the search criteria applied in this rapid assessment, was limited. Further engagement with industry and other stakeholders is an important next step to help identify and test further synthesis steps, including:

- Outputs: are there other products, tools, services or audiences that could add to the information captured in the rapid assessment search criteria?
- Further questions:
    - Can more data on fertiliser rates and pesticide use within individual commodities be located (as exampled for some commodity types)?
    - Is there further information or does opportunity exist to leverage field trials to capture additional information relating to water, sediments, nutrients and pesticides to add to the data presented in Appendix 2?
    - Could further qualitative information help generate hypotheses that might be further tested by quantitative methods?
    - How could the information gathered in this project be used to assist decision-making and impact?
    - How to design a future work program which considers measurements of pollutant losses and the reporting of data in a manner that is comparable, can be easily interpreted and is consistent across classifications?
- Impacts: conceptual advances, capacities, networks to address the agreed knowledge gaps, new or improved capacity to relate and/or integrate outputs to assist decision-making

We acknowledge that engagement with industry and stakeholders is an important next step, since “a focus on those engaged with the use of synthesis will provide critical insight into whether or not a particular initiative had an impact in a given context and ask the critical question as to whether the nature of the research as ‘synthesis’ inherently increased its utility. Understanding such perspectives is vital to improve the design of synthesis for impact, as their perspectives on the value of synthesis research and its role in decision-making are likely to be very different from those of technical experts” (Wyborn et al. 2018).

Reference list

Project rationale and objectives

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J., Waterhouse, J., 2017. Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. Brisbane.

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J.E., Star, M., Thorburn, P., Rolfe, J., Ronan, M., Taylor, B., Kroon, F., 2017. 2017 Scientific Consensus Statement: Land Use Impacts on Great Barrier Reef Water Quality and Ecosystem Condition.

Project scope

ABS (2021a) ‘Agricultural Commodities, Australia ‘Agricultural commodities, Australia and state/territory and NRM regions - 2019-20’ [data set], <https://www.abs.gov.au/statistics/industry/agriculture/agricultural-commodities-australia/2019-20> [URL], accessed 20 May 2021.

ABS (2021b) ‘Water use on Australian farms, Australia, state/territory and NRM and MDB regions - 2019-2020' [data set], <*https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms/latest-release*> [URL], accessed 20 May 2021.

Applied Agricultural Remote Sensing Centre (2021) ‘Australian Tree Crop Map’ [data set], < <https://www.arcgis.com/home/item.html?id=942d52abe9104273b2a3a5a33762672f#overview> [URL], accessed 20 May 2021.

QLUMP (2019) ‘Land use mapping - 1999 to Current – Queensland’ [data set], <http://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q=%22Land%20use%20mapping%20-%201999%20to%20Current%20-%20Queensland%22> [URL], Department of Environment and Science, accessed 20 February 2021.

Wyborn, C., Louder, E., Harrison, J., Montambault J., Montana J., Ryan, M., Bednarek, A., Nesshöver, C., Pullin, A., Reed, M., Dellecker, E., Kramer, J., Boyd, J., Dellecker, A., Hutton, J., 2018. Understanding the Impacts of Research Synthesis. Environmental Science and Policy. 86, 72–84. https://doi.org/10.1016/j.envsci.2018.04.013

Production from dryland agriculture and plantations

Bureau of Meteorology, 2019a. Regional Weather and Climate Guide: Wet Tropics.

Bureau of Meteorology, 2019b. Regional Weather and Climate Guide: Fitzroy Basin.

Bureau of Meteorology, 2019c. Regional Weather and Climate Guide: Burdekin.

Bureau of Meteorology, 2019d. Regional Weather and Climate Guide: Burnett Mary.

Bureau of Meteorology, 2019e. Regional Weather and Climate Guide: Cape York.

Bureau of Meteorology, 2019f. Regional Weather and Climate Guide: Reef Catchments.

Cereals and Pulses

Angus, J.F., Grace, P.R., 2017. Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. Soil Res. 55, 435–450. https://doi.org/10.1071/SR16325

Bell, M., Lester, D., Smith, L., Want, P., 2012. Increasing complexity in nutrient management on clay soils in the northern grain belt – nutrient stratification and multiple nutrient limitations., in: Proceedings, 16th Australian Agronomy Conference. pp. 14–18.

Bell, M., Moody, P., Klepper, K., Dave Lawrence, 2010. The challenge to sustainability of broadacre grain cropping systems on clay soils in northern Australia, in: World Congress of Soil Science. pp. 302–305.

Carroll, C., 2004. Minimising the environmental impacts of grain cropping at a paddock to neighbourhood catchment scale.

Carroll, C., Halpin, M., Burger, P., Bell, K., Sallaway, M.M., Yule, D.F., 1997. The effect of crop type, crop rotation, and tillage practice on runoff and soil loss on a Vertisol in central Queensland. Aust. J. Soil Res. 35, 925–939. https://doi.org/10.1071/S96017

Cogle, A.L., Keating, M.A., Langford, P.A., Gunton, J., Webb, I.S., 2011. Runoff, soil loss, and nutrient transport from cropping systems on Red Ferrosols in tropical northern Australia. Soil Res. 49, 87–97. https://doi.org/10.1071/SR10069

Cowie, B.A., Thornton, C.M., Radford, B.J., 2007. The Brigalow Catchment Study: I. Overview of a 40-year study of the effects of land clearing in the brigalow bioregion of Australia. Aust. J. Soil Res. 45, 479–495. https://doi.org/10.1071/SR07063

Cox, H.W., Strong, W.M., 2017. The Nitrogen book: principles of soil nitrogen fertility management in central Queensland farming systems. Brisbane, Australia.

Cox, H.W., Strong, W.M., Lack, D.W., Kelly, R.M., 1998. Profitable double-cropping rotations involving cereals and pulses in central Queensland, in: Proceedings of the 9th Australian Agronomy Conference. Charles Sturt University, Wagga Wagga.

Eames, H., Collins, R., 2017. Grains best management practices: Delivering productivity and sustainability outcomes for the central Queensland grains industry. Rural Ext. Innov. Syst. J. 13, 121–126.

Elledge, A., Thornton, C., 2017. Effect of changing land use from virgin brigalow (Acacia harpophylla) woodland to a crop or pasture system on sediment, nitrogen and phosphorus in runoff over 25 years in subtropical Australia. Agric. Ecosyst. Environ. 239, 119–131. https://doi.org/10.1016/j.agee.2016.12.031

Freebairn, D., 2014. Quantifying impacts of management on sediment, nutrient and pesticide loss from grain farms.

GRDC, 2017. Farm Practices Survey - 2016.

GRDC, 2016. Chickpeas Northern Region - GrowNotesTM 53, 1689–1699.

Hargreaves, P.., Noble, R.., 1993. Measurement of herbicide residues in soils from reduced tillage sites.

Hulugalle, N.R., Rohde, K.W., Yule, D.F., 2002. Cropping systems and bed width effects on runoff, erosion and soil properties in a rainfed Vertisol. L. Degrad. Dev. 13, 363–374. https://doi.org/10.1002/ldr.510

Lewis, S., Bainbridge, Z., Stevens, T., Garzon-Garcia, A., Chen, C., Bahadori, M., Burton, J., Rezaei Rashti, M., James, C., Smithers, S., Olley, J., 2020. What's really damaging the Reef? Tracing the origin and fate of the ecologically detrimental sediment and associated bioavailable nutrients. Cairns, Australia.

Lewis, S., Packett, B., Dougall, C., Brodie, J., Bartley, R., Silburn, M., Packett, R., 2015. Fitzroy Sediment Story. Synth. Rep. to Fitzroy Basin Assoc. as part Water Qual. Improv. Plan Process 38pp.

Loughran, R.J., Elliott, G.L., 1996. Rates of soil erosion in Australia determined by the caesium-137 technique: A national reconnaissance survey. IAHS-AISH Publ. 236, 275–282.

Murphy, T., Dougall, C., Burger, P., Carroll, C., 2013. Runoff water quality from dryland cropping on Vertisols in Central Queensland, Australia. Agric. Ecosyst. Environ. 180, 21–28. https://doi.org/10.1016/j.agee.2011.07.023

Packett, R., 2014. Pesticide Dynamics in the Great Barrier Reef Catchment and Lagoon: Management Practices (Grazing, Bananas and Grain Crops) and Risk Assessments (Project RRRD038). Tebuthiuron Management in Grazing Lands (Subproject 2). Report to the Reef Rescue Water Qual. Reef and Rainforest Research Centre Limited, Cairns.

Pulse Australia, 2021. Best Management Practice - Chickpea Production: Northern Region [WWW Document]. URL http://www.pulseaus.com.au/growing-pulses/bmp/chickpea/northern-guide (accessed 5.10.21).

Queensland Government, 2018. Agricultural Land Management Practice Adoption - Methods - Reef Water Quality Report Card 2017 and 2018 - Reef 2050 Water Quality Improvement Plan.

Rhode, K.W., Yule, D.F., 1995. Land management systems including controlled traffic rotations and erosion control for dryland cotton production. Proc. Natl. Control. Traffic Conf. 13–14 Sept. 1995, Rockhampton, Queensland.

Rogusz, D., Burger, P., 2017. Paddock to Reef water quality monitoring from dryland grains cropping and grazing land use within a nested catchment design - Final Report 2013-2016.

Rogusz, D., Rohde, K., Carroll, C., Burger, P., 2013. Paddock to sub-catchment scale water quality monitoring from dryland grains cropping and grazing. Final Report 2009-2012 Wet Seasons.

Rogusz, D.J., 2019. Paddock to sub-catchment scale water quality monitoring of dryland grain cropping and grazing land uses. Gordonstone Creek catchment monitoring – Fitzroy Region. Final Report. 2016–2018. Queensland.

Sallaway, M.M., Lawson, D., Yule, D.F., 1988. Ground cover during fallow from wheat, sorghum and sunflower stubble under three tillage practices in Central Queensland. Soil Tillage Res. 12, 347–364. https://doi.org/10.1016/0167-1987(88)90045-1

Silburn, D.M., Cowie, B.A., Thornton, C.M., 2009. The Brigalow Catchment Study revisited: Effects of land development on deep drainage determined from non-steady chloride profiles. J. Hydrol. 373, 487–498. https://doi.org/10.1016/j.jhydrol.2009.05.012

Star, M., Beutel, T., Schrobback, P., Rolfe, J., Ellis, R., 2015. Prioritisation of neighbourhood catchments: Recommendations, gaps and future research.

Star, M., Beutel, T., Schrobback, P., Rolfe, J., Mccosker, K., 2016. Prioritisation of neighbourhood catchments in the Fitzroy Basin.

State of Queensland, University of Southern Queensland, 2017. ARM online [WWW Document]. URL http://www.armonline.com.au/ (accessed 5.10.21).

Thorburn, P.J., Wilkinson, S.N., 2013. Conceptual frameworks for estimating the water quality benefits of improved agricultural management practices in large catchments. Agric. Ecosyst. Environ. 180, 192–209. https://doi.org/10.1016/J.AGEE.2011.12.021

Thornton, C.M., Cowie, B.A., Freebairn, D.M., Playford, C.L., 2007. The Brigalow Catchment Study: II Clearing brigalow (Acacia harpophylla) for cropping or pasture increases runoff. Aust. J. Soil Res. 45, 496–511. https://doi.org/10.1071/SR07064

Waterhouse, J., Flint, N., Johnson, J., 2015. Fitzroy WQIP Supporting Studies: Key findings, gaps and recommendations.

Yule, D., Rohde, K., 1996. Runoff and soil loss from dryland cotton rotations, in: Proceedings of 8th Australian Cotton Conference. Broadbeach, Queensland, pp. 469–471.

Irrigated cotton

Antille, D.L., Moody, P.W., 2021. Nitrogen use efficiency indicators for the Australian cotton, grains, sugar, dairy and horticulture industries. Environ. Sustain. Indic. 10, 100099. https://doi.org/10.1016/j.indic.2020.100099

Bartley, R., Speirs, W.J., Ellis, T.W., Waters, D.K., 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. Mar. Pollut. Bull. 65, 101–116. https://doi.org/10.1016/j.marpolbul.2011.08.009

Carroll, C., Halpin, M., Bell, K., Mollison, J., 1995. The effect of furrow length on rain and irrigation- induced erosion on a vertisol in Australia. Aust. J. Soil Res. 33, 833–850. https://doi.org/10.1071/SR9950833

Connolly, R., Kennedy, I., Silburn, D., Simpson, B., Freebairn, D., 1998. ‘Exploring farms design and management options with modelling’, in NJ Schofield and VE Edge (eds), Minimising the impact of pesticides on the riverine environment: key findings from research with the cotton industry– 1998 Conference, Occasional Paper 23/9. Canberra, Australia.

Connolly, R.D., Carroll, C., Francis, J., Silburn, D.M., Simpson, B., Freebairn, D.M., 1999. A simulation study of erosion in the Emerald Irrigation Area. Soil Res. 37, 479. https://doi.org/10.1071/S98096

CRDC, 2020a. 2020 Grower Survey.

CRDC, 2020b. Australian Cotton Production Manual 2020.

CRDC, 2019. Australian Cotton Sustainability Report 2019.

CRDC, 2018. NUTRIpak - A practical guide to cotton nutrition. CRDC.

Eberhard, R., Thorburn, P., Rolfe, J., Taylor, B., Ronan, M., Weber, T., Flint, N., Kroon, F., Brodie, J., Waterhouse, J., Silburn, M., Bartley, R., Davis, A., Wilkinson, S., Lewis, S., Star, M., Poggio, M., Windle, J., Marshall, N., Hill, R., Maclean, K., Lyons, P., Robinson, C., Adame, F., Selles, A., Griffiths, M., Gunn, J., McCosker, K., 2017. Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 4: Management options and their effectiveness.

Goyne, P.J., McIntyre, G.T., 2003. Stretching water - Queensland’s water use efficiency cotton and grains adoption program. Water Sci. Technol. 48, 191–196. https://doi.org/10.2166/wst.2003.0440

Grundy, P., Yeates, S., Grundy, T., 2012. NORpak: Cotton production and management guidelines for the Burdekin and north Queensland coastal dry tropics region.

Hulugalle, N.R., Rohde, K.W., Yule, D.F., 2002. Cropping systems and bed width effects on runoff, erosion and soil properties in a rainfed Vertisol. L. Degrad. Dev. 13, 363–374. https://doi.org/10.1002/ldr.510

Lewis, S., Bartley, R., Wilkinson, S., Bainbridge, Z., Henderson, A.E., Irvine, S.A., Brodie, J., 2021. Land use change in the river basins of the Great Barrier Reef, 1860 to 2018: Constructing foundational records to interpret environmental history across the catchment to reef continuum. Mar. Pollut. Bull. 166, 112193. https://doi.org/10.1016/j.marpolbul.2021.112193

Lovett, S., Price, P., Lovett, J., 2003. Managing Riparian Lands in the Cotton Industry, Cotton Research and Development Corporation.

Maas, S., Redfern, R., 2020. Cotton Pest Management Guide 2020 - 2021.

McHugh, A.D., Bhattarai, S., Lotz, G., Midmore, D.J., 2008. Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides. Agron. Sustain. Dev. 28, 507–519. https://doi.org/10.1051/agro:2008034

myBMP, 2021. Best Management Practices for Australian Cotton [WWW Document]. URL https://www.mybmp.com.au/

Nachimuthu, G., Webb, A.A., 2016. On-farm soil conservation measures in cotton farming systems of Australia: A sustainability analysis. J. Soil Water Conserv. 71, 75A-80A. https://doi.org/10.2489/jswc.71.3.75A

Noble, R.M., Duivenvoorden, L.J., Rummenie, S.K., Long, P.E., Fabbro, L.D., 1996. Downstream Effects of Land Use in the Fitzroy Catchment.

QDPIF, 2009. Final Report. Rural Water Use Efficiency 3. Best Practice Water Use and Irrigation in Irrigated Cotton and Grain. Toowoomba, Queensland.

Radcliffe, J.C., 2002. Pesticide use in Australia. Parkville, VIC.

Rochester, I.J., 2007. Nutrient uptake and export from an Australian cotton field. Nutr. Cycl. Agroecosystems 77, 213–223. https://doi.org/10.1007/s10705-006-9058-2

Roth, G., Harris, G., Gillies, M., Montgomery, J., Wigginton, D., 2013. Water-use efficiency and productivity trends in Australian irrigated cotton: A review. Crop Pasture Sci. 64, 1033–1048. https://doi.org/10.1071/CP13315

Silburn, D.M., Foley, J.L., Biggs, A.J.W., Montgomery, J., Gunawardena, T.A., 2013a. The Australian cotton industry and four decades of deep drainage research: A review. Crop Pasture Sci. 64, 1049–1075. https://doi.org/10.1071/CP13239

Silburn, D.M., Foley, J.L., deVoil, R.C., 2013b. Managing runoff of herbicides under rainfall and furrow irrigation with wheel traffic and banded spraying. Agric. Ecosyst. Environ. 180, 40–53. https://doi.org/10.1016/j.agee.2011.08.018

Silburn, D.M., Glanville, S.F., 2002. Management practices for control of runoff losses from cotton furrows under storm rainfall. I. Runoff and sediment on black Vertosol. Aust. J. Soil Res. 40, 1–20. https://doi.org/https://doi.org/10.1071/SR00082

Simpson, B.W., Hargreaves, P.A., Noble, R.M., Thomas, E., Kuskopf, B., Carroll, C., 1998. Pesticide behaviour on-farm: persistence and off-site transport (Queensland), in: Schofield, N.J., Edge, V.E. (Eds.), Minimising the Impact of Pesticides on the Riverine Environment: Key Findings from Research with the Cotton Industry'. Canberra, Australia, pp. 38–43.

Smith, J., Carroll, C., McHugh, J., 2003. Subsurface Drip And Furrow Experiment.

Smith, R.J., Raine, S.R., Minkevich, J., 2005. Irrigation application efficiency and deep drainage potential under surface irrigated cotton. Agric. Water Manag. 71, 117–130. https://doi.org/10.1016/j.agwat.2004.07.008

Trindall, J., Roth, G., Williams, S., Harris, G., Wigginton, D., 2012. The Australian cotton water story… A decade of Research & Development 2002–12.

Waters, D., 2001. Best Management Practices to Minimise Pollutant Transport from Cotton Production Systems.

Yeates, S., 2015. Assisting cotton industry diversification in coastal NQ & tropical Australia.

Yeates, S.J., Strickland, G.R., Grundy, P.R., 2013. Can sustainable cotton production systems be developed for tropical northern Australia. Crop Pasture Sci. 64, 1127–1140. https://doi.org/10.1071/CP13220

Bananas

Armour, J., 2018. Nutrient Management Plan for the Banana Industry (of north Queensland).

Armour, J., Davis, A., Masters, B., Whitten, M., 2012. Paddock scale water quality monitoring of banana and sugarcane management practices, Summary report 2010 - 2013 wet seasons Wet Tropics Region. Runoff and deep drainage in banana cropping. 8.

Armour, J., Mortimore, C., Pathania, N., Wiltshire, N., Daniells, J., Masters, B., Reghenzani, J., 2014. Minimising off-farm movement of nitrogen in the north Queensland banana industry. Report to the Reef Rescue Research & Development Program. Cairns, Australia.

Armour, J.D., Hateley, L.R., Pitt, G.L., 2009. Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in the Tully - Murray basin. Mar. Freshw. Res. 60, 1091–1096. https://doi.org/10.1071/MF08345

Armour, J.D., Nelson, P.N., Daniells, J.W., Rasiah, V., Inman-Bamber, N.G., 2013. Nitrogen leaching from the root zone of sugarcane and bananas in the humid tropics of Australia. Agric. Ecosyst. Environ. 180, 68–78. https://doi.org/10.1016/J.AGEE.2012.05.007

Australian Banana Growers' Council, 2021. Economic Contribution [WWW Document]. URL https://abgc.org.au/our-industry/economic-contribution/ (accessed 5.23.21).

Australian Banana Growers' Council, 2017. North Queensland Banana Industry Water quality strategy 2017 – 2020.

Bagshaw, J., Lindsay, S., 2009. Developing sustainable banana production systems: A case study from tropical Australia. Acta Hortic. 831, 23–30. https://doi.org/10.17660/ActaHortic.2009.831.2

Bahadori, M., Chen, C., Lewis, S., Rashti, M.R., Cook, F., Parnell, A., Esfandbod, M., Stevens, T., 2020. Tracing the sources of sediment and associated particulate nitrogen from different land uses in the Johnstone River catchment, Wet Tropics, north-eastern Australia. Mar. Pollut. Bull. 157, 111344. https://doi.org/10.1016/j.marpolbul.2020.111344

Bahadori, M., Chen, C., Lewis, S., Rezaei Rashti, M., Cook, F., Parnell, A., Esfandbod, M., Boyd, S., 2019. A novel approach of combining isotopic and geochemical signatures to differentiate the sources of sediments and particulate nutrients from different land uses. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2018.11.084

Bainbridge, Z.T., Brodie, J.E., Faithful, J.W., Sydes, D.A., Lewis, S.E., 2009. Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully - Murray Basin, Queensland, Australia. Mar. Freshw. Res. 60. https://doi.org/10.1071/MF08333

Bartley, R., Speirs, W.J., Ellis, T.W., Waters, D.K., 2012. A review of sediment and nutrient concentration data from Australia for use in catchment water quality models. Mar. Pollut. Bull. 65, 101–116. https://doi.org/10.1016/j.marpolbul.2011.08.009

Bhattarai, S.P., Midmore, D.J., 2015. Advanced drip and optimised furrow irrigation to minimise sediment, nutrient and pesticide losses to the environment through deep drainage and run-off from sugarcane and banana industries in northern Queensland, Report to the Reef Rescue Water Quality Research & Development Program. Cairns.

Brodie, J.E., Kroon, F.J., Schaffelke, B., Wolanski, E.C., Lewis, S.E., Devlin, M.J., Bohnet, I.C., Bainbridge, Z.T., Waterhouse, J., Davis, A.M., 2012. Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. Mar. Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2011.12.012

Carr, M.K.V., 2009. The water relations and irrigation requirements of banana (Musa SPP.). Exp. Agric. https://doi.org/10.1017/S001447970900787X

Council of Agricultural Science and Technology, 1992. Preparing US Agriculture for Global Climate Change. Task Force Report, No. 119. Waggoner PE Chair [WWW Document]. URL http://www.ciesin.org/docs/004-181/004-181.html (accessed 5.23.21).

DAF, 2016. Banana Best Management Practices - Environmental guidelines for the Australian Banana Industry.

Faithful, J., Finlayson, W., 2005. Water quality assessment for sustainable agriculture in the Wet Tropics - A community-assisted approach, in: Marine Pollution Bulletin. https://doi.org/10.1016/j.marpolbul.2004.11.007

Food and Agriculture Organization of the United Nations, 2021. World Banana Forum [WWW Document]. URL http://www.fao.org/world-banana-forum/projects/good-practices/water-footprint/en/

Fraser, G., Rohde, K., Silburn, M., 2017. Fertiliser management effects on dissolved inorganic nitrogen in runoff from Australian sugarcane farms. Environ. Monit. Assess. 189. https://doi.org/10.1007/s10661-017-6115-z

Freshcare, 2021. Reef Assured – Bananas. [WWW Document]. URL https://www.freshcare.com.au/resources/reef-bananas/ (accessed 5.23.21).

Growcom, 2021. Water for profit. Benchmark - Irrigating bananas in North Queensland.

Growcom Australia, 2021. Hort360 Reef Certification Interpretive Guideline. Fortitude Valley, Qld.

Harvey, S., Cook, S., Poggio, M., 2018. Economic assessment of best management practices for banana growing, Report to the Department of Environment and Science through funding from the Reef Water Quality Science Program, RP140B Final synthesis report. Queensland.

Hateley, L., 2014. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef catchments, Wet Tropics NRM region, Technical Report Volume 3.

Hateley, L., Armour, J., Pitt, G., Cogle, L., 2020. Use of SEdNET model to establish sediment export targets for catchments of the wet tropics draining to the Great Barrier Reef. MODSIM 2005 - Int. Congr. Model. Simul. Adv. Appl. Manag. Decis. Making, Proc. 1154–1160.

Hort Innovation, 2020. Banana Strategic Agrichemical Review Process.

Hunter, H.M., Walton, R.S., 2008. Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef, Australia. J. Hydrol. 356, 131–146. https://doi.org/10.1016/j.jhydrol.2008.04.003

Lewis, S., Brodie, J., Andersen, J., Armour, J., Baillie, C., Davis, A., Eaglesham, G., Elledge, A.E., Fillols, E., Flores, F., Gallen, C., Kookana, R., Mchugh, J., Masters, B., Mercurio, P., Mortimore, C., Mueller, J.F., Negri, A.P., Brien, D.O., Oliver, D., Packett, B., Paxman, C., Rojas-ponce, S., Shaw, M., Silburn, D.M., Smith, R., Turner, R., Thornton, C.M., Warne, M., 2014. Pesticide Dynamics in the Great Barrier Reef Catchment and Lagoon : Management Practices (sugar, grazing, bananas) and Risk Assessments: Overview Report for Project Number RRRD037 and RRRD038.

Lewis, S.E., Bartley, R., Wilkinson, S.N., Bainbridge, Z.T., Henderson, A.E., James, C.S., Irvine, S.A., Brodie, J.E., 2021. Land use change in the river basins of the Great Barrier Reef, 1860 to 2019: A foundation for understanding environmental history across the catchment to reef continuum. Mar. Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2021.112193

Lindsay, S., Campagnolo, D., Daniells, J., Evans, D., Goebel, R., Gunther, M., Lemin, C., Pattinson, T., Peterson, R., Pinese, B., Wharton, D., Kernot, I., 1998. Tropical Banana Information Kit. Agrilink, your growing guide to better farming guide. Manual. Agrilink Series QAL9807. Brisbane, Queensland.

Masters, B., Mortimore, C., Armour, J., Lewis, S., 2015. Pesticide runoff and deep drainage in banana cropping Caring. Report to the Reef Rescue Water Quality Research & Development Program.

Masters, B., Mortimore, C., Tahir, N., Fries, J., Armour, J., 2017. Paddock-scale water quality monitoring of banana cropping management practices. 2010-2015 Final Summary Report. Wet Tropics region.

McKergow, L.A., Prosser, I.P., Grayson, R.B., Heiner, D., 2004. Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 1. Riparian hydrology. Aust. J. Soil Res. 42, 473–484. https://doi.org/10.1071/SR02155

McKergow, L A, Prosser, I.P., Grayson, R.B., Heiner, D., 2004. Performance of grass and rainforest riparian buffers in the wet tropics, Far North Queensland. 2. Water quality. Aust. J. Soil Res. 42, 485–498. https://doi.org/https://doi.org/10.1071/SR02156

Mitchell, A., Reghenzani, J., Faithful, J., Furnas, M., Brodie, J., 2009. Relationships between land use and nutrient concentrations in streams draining a “wet-tropics” catchment in northern Australia. Mar. Freshw. Res. 60, 1097–1108. https://doi.org/10.1071/MF08330

Mitchell, A.W., Reghenzani, J.R., Furnas, M.J., 2001. Nitrogen levels in the Tully River - A long-term view. Water Sci. Technol. 43, 99–105. https://doi.org/10.2166/wst.2001.0516

Office of the Great Barrier Reef, 2019a. Reef protection regulations. Farming in Reef catchments. Erosion and sediment control guide (Agricultural environmentally relevant activity standard for banana cultivation).

Office of the Great Barrier Reef, 2019b. Reef protection regulations. Farming in Reef catchments. Fertiliser placement guide (Agricultural environmentally relevant activity standard for banana cultivation).

Office of the Great Barrier Reef, 2019c. Reef protection regulations. Farming in Reef catchments. Prescribed methodology for banana cultivation (Agricultural environmentally relevant activity standard for banana cultivation).

Peoples, M., Freney, J., Mosier, A., 1995. Minimizing gaseous losses of nitrogen, in: Bacon, P. (Ed.), Nitrogen Fertilization in the Environment. Marcel Dekker, New York, USA, pp. 565–602.

Prasertsak, P., Freney, J.R., Saffigna, P.G., Denmead, O.T., Prove, B.G., 2001. Fate of urea nitrogen applied to a banana crop in the wet tropics of Queensland. Nutr. Cycl. Agroecosystems. https://doi.org/10.1023/A:1009806826141

Queensland Government, 2016. Queensland’s banana industry [WWW Document]. URL https://www.business.qld.gov.au/industries/farms-fishing-forestry/agriculture/crop-growing/banana-industry (accessed 5.23.21).

Rasiah, V., Armour, J.D., Cogle, A.L., Florentine, S.K., 2010. Nitrate import-export dynamics in groundwater interacting with surface-water in a wet-tropical environment. Aust. J. Soil Res. 48, 361–370.

https://doi.org/10.1071/SR09120

Rasiah, V., Armour, J.D.D., 2001. Nitrate accumulation under cropping in the Ferrosols of Far North Queensland wet tropics. Aust. J. Soil Res. 39, 329–341. https://doi.org/10.1071/SR99133

Shaw, M., Furnas, M.J., Fabricius, K., Haynes, D., Carter, S., Eaglesham, G., Mueller, J.F., 2010. Monitoring pesticides in the Great Barrier Reef. Mar. Pollut. Bull. https://doi.org/10.1016/j.marpolbul.2009.08.026

SMART Fertiliser Software, 2020. Growing Banana Trees - Banana Fertilizer Software Requirements [WWW Document]. URL https://www.smart-fertilizer.com/articles/banana-fertilizer-requirements/ (accessed 5.23.21).

Terrain NRM, 2015. Wet Tropics Water Quality Improvement Plan 2015-2020.

Wakelin, S.A., Nelson, P.N., Armour, J.D., Rasiah, V., Colloff, M.J., 2011. Bacterial community structure and denitrifier (nir-gene) abundance in soil water and groundwater beneath agricultural land in tropical North Queensland, Australia. Soil Res. https://doi.org/10.1071/SR10055

Macadamias

ABC News, 2021. Macadamia nut 'trampolines' a potential game changer for the industry. [WWW Document]. URL https://www.abc.net.au/news/rural/2021-02-28/macadamia-nut-trampolines-a-potential-game-changer-for-industry/13186358 (accessed 03.05.2021).

Cox J, Dalby T, Morris S, Keen B, Slavich P., 2010. Improving soil and orchard floor management in macadamias - Final report MC05001.

Firth DJ, and McFayden LM., 1999. Groundcovers for erosion control in Macadamias - Stage 2: Evaluation of best selections and screening of new species. Australian Macadamia Society 1999 Conference Report.

Growcom, 2021. Best practice soil management benefits Sunshine Coast macadamia farm [WWW Document]. URL https://www.growcom.com.au/_uploads/HORT360/FVNNOV_HORT360_Best-practice-soil-management-benefits-Sunshine-Coast-macadamia-farm.pdf (accessed 4.12.21).

NSW DPI, 2021. Macadamia Plant Protection Guide 2021–22. [WWW Document]. URL https://australianmacadamias.org/industry/resources/macadamia-plant-protection-guide-2021-2022-nsw-dpi-managment-guide

O'Hare P, Stephenson R, Quinlan K, Vock N., 2004. Macadamia Grower's Handbook - Chapter 4: Additional information on some key issues. (Department of Primary Industries and Fisheries in collaboration with New South Wales Department of Primary Industries and the Australian Macadamia Society, Nambour, Queensland.)

Reid G., 2002. Soil and nutrient loss in Macadamia lands: A pilot study, Horticulture Australia Report MC 98011.

State of Queensland, 2020. Macadamia industry benchmark report – 2009 to 2019 seasons. [WWW Document]. URL http://era.daf.qld.gov.au/id/eprint/7585/ (accessed 06.30.2021).

Stork PR, Bennett FR, Bell MJ, Moody PW., 2007. Benchmarking pesticides and nutrients in horticulture and new cane farming systems (AG05). 1–53. doi:10.13140/RG.2.1.2126.6000.

Stork PR, Lyons DJ, Bell MJ., 2009. Losses of nitrogen in surface runoff from a plantation horticulture farm in coastal Queensland, Australia. *Soil Research* **47**, 565. doi:10.1071/SR08238.

Stork PR, Lyons DJ, Stork PR, Lyons DJ., 2012. Phosphorus loss and speciation in overland flow from a plantation horticulture catchment and in an adjoining waterway in coastal Queensland, Australia. *Soil Research* **50**, 515–525. doi:10.1071/SR12042.

Wehr JB, Smith T., 2016 Review of macadamia orchard nutrition.

Avocados

DAF Queensland, 2013a. Guide to irrigation requirements in Australia. [WWW Document]. URL *https://avocado.org.au/bpr-articles/guide-irrigation-requirements-australia/*.

DAF Queensland, 2013b. Australian Avocado Best Practice Resource - Growing - Nutrition. [WWW Document]. URL *https://avocado.org.au/best-practice-resource/growing/*. https://avocado.org.au/best-practice-resource/growing/nutrition/.

Growcom, 2021. Water for Profit. Benchmark - Irrigating Avocados in Lower Burnett.

Newett S, Rigden P, Carr B., 2018. Avocado Plant Nutrition Review.

Vegetables

Australian Bureau of Statistics, 2020. Water Use on Australian Farms-2018-19 [WWW Document]. URL https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms/latest-release

Carey, B., Stone, B., Norman, P., Shilton, P., 2015. Chapter 12 Soil Conservation in horticulture, in: Soil Conservation Guidelines for Queensland. Department of Science, Information Technology and Innovation, Brisbane, Australia.

Fullelove, G., Wright, R., Meurant, N., Barnes, J., O’Brien, R., Lovatt, J., 1998. Tomato Information Kit. Agrilink, your growing guide to better farming guide.

Harper, S., 2014. Environmental effects of vegetable production on sensitive waterways.

Harper, S., Menzies, N., 2006. Potential pollution of the Great Barrier Reef lagoon through horticultural fertiliser loss.

Heisswolf, S., Wright, R., Moody, P., Pattison, T., 2010. Vegetable production in the dry tropics - Nutrient and soil management strategies from Queensland Australia. Acta Hortic. 852, 97–106. https://doi.org/10.17660/actahortic.2010.852.10

Henderson, C., 2006. Maximising returns from water in the Australian vegetable industry Queensland.

Hort Innovation, 2020. Australian Horticulture Statistics Handbook 2019/20 - Vegetables.

Jackson, K., Kerr, J., Kilpatrick, J., Henderson, C., Lovatt, J., 1997. Potato Information Kit. Agrilink, your growing guide to better farming guide.

Loader, L., Harper, S., Amante, V., Jackson, K., Buchanan, P., 1999. Sweet Potato Information Kit. Agrilink, your growing guide to better farming guide.

Meurant, N., Wright, R., Olsen, J., Fullelove, G., Lovatt, J., 1999. Capsicum and Chilli Information Kit. Agrilink, your growing guide to better farming guide.

Nachimuthu, G., Halpin, N., Bell, M., 2017. Impact of Practice Change on Runoff Water Quality and Vegetable Yield—An On-Farm Case Study. Agriculture 7, 30. https://doi.org/10.3390/agriculture7030030

Nachimuthu, G., Halpin, N., Bell, M., 2013. Paddock Scale Water Quality Monitoring of Vegetable-Sugarcane and Legume- Sugarcane Farming Systems Summary report.

Olsen, J., 1992. Investigation of the effects of planting density and nutrition on marketable yield of capsicums.

Pung, H., 2003. A survey approach to investigate the soil factors associated with the productivity and sustainability of vegetable production in Australia Dr Hoong Pung.

Stork, P.R., Bennett, F.R., Bell, M.J., Moody, P.W., 2007. Benchmarking pesticides and nutrients in horticulture and new cane farming systems (AG05) 1–53. https://doi.org/10.13140/RG.2.1.2126.6000

Stork, P.R., Jerie, P.H., Callinan, A.P., 2003. Subsurface drip irrigation in raised bed tomato production. I. Nitrogen and phosphate losses under current commercial practice. Aust. J. Soil Res. 41, 1283–1304. https://doi.org/https://doi.org/10.1071/SR02145

Wright, R., Deuter, P., Napier, T., Dimsey, R., Duff, J., Walsh, B., Hill, L., Learmonth, S., Geitz, G., Heisswolf, S., Nolan, B., Olsen, J., Meurant, N., 2005. Sweet Corn Information Kit. Agrilink, your growing guide to better farming guide.

Pineapples

Abel, R., 2021. Erosion Management - Why Control Sediment Movement on Farm?, in: Combined South-East Queensland and Wide Bay Study Group. Australian Pineapples, Brisbane, pp. 17–21.

Abel, R., 2020. Nitrogen Use Efficiency in Pineapple Farming Systems.

Australian Pineapples, 2020. SA04WB-05 - Research Topic 4: Pesticide Management.

Australian Pineapples, 2019a. SA05WB-03.

Australian Pineapples, 2019b. SA03SEQ-04 - Research Topic 3: Pre and Post Nutrition Management.

Carey, B., Stone, B., Norman, P., Shilton, P., 2015. Chapter 12 Soil Conservation in horticulture, in: Soil Conservation Guidelines for Queensland. Department of Science, Information Technology and Innovation, Brisbane, Australia.

Ciesiolka, C., Scott, C., Sinclair, E., McPherson, D., K, H., n.d. Is there a sustainable system for pineapple farming.

Ciesiolka, C.A.A., Coughlan, K.J., Rose, C.W., Smith, G.D., 1995. Erosion and hydrology of steeplands under commercial pineapple production. Soil Technol. 8, 243–258. https://doi.org/10.1016/0933-3630(95)00023-2

Coughlan, K.J., Rose, C.W., 1997. A New Soil Conservation Methodology and Application to Cropping Systems in Tropical Steeplands. Canberra, Australia.

DAF, 2014. Pineapples [WWW Document]. URL https://www.daf.qld.gov.au/business-priorities/agriculture/plants/fruit-vegetable/fruit-vegetable-crops/pineapples (accessed 5.23.21).

DAF, 2013. Land requirements for growing pineapple [WWW Document]. URL https://www.daf.qld.gov.au/business-priorities/agriculture/plants/fruit-vegetable/fruit-vegetable-crops/pineapples/land-requirements-pineapple (accessed 5.23.21).

Griffin, L., 2020a. Pre-plant fertiliser rate trials at Littabella Pines.

Griffin, L., 2020b. Littabella Pines : A Bioreactor Case Study.

Growcom, 2021. Hort360 Reef Certification Management Practices. Fortitude Valley, Qld.

Growcom, 2020. Soils and nutritiion program provides a wealth of information to horticulture growers [WWW Document]. URL https://www.growcom.com.au/2020/12/16/soils-and-nutrition-program-provides-a-wealth-of-information-to-horticulture-growers/ (accessed 5.23.21).

Hort Innovation, 2020. Australian Horticulture Statistics Handbook 2019/20 - Fruit. Sydney, Australia.

Hort Innovation, 2019. Pineapple - strategic agrichemical review process (SARP) - HI project MT18007.

Hort Innovation, 2017. Pineapple Strategic Investment Plan 2017-2021. Sydney, Australia.

Newett, S., Sanewski, G., Wolens, T., Tanguilig, V., Christensen, D., Queensland, F., Jorgensen, K., Petzler, A., Wroe, V., 2006. Pineapple Best Practice Manual.

Palis, R.G., Rose, C.W., Saffigna, P.G., 1997. Soil erosion and nutrient loss. IV. Effect of slope length on runoff, sediment yield, and total nitrogen loss from steep slopes in pineapple cultivation. Aust. J. Soil Res. 35, 907–923. https://doi.org/10.1071/S92061

Plant Health Australia, 2021. Pineapples [WWW Document]. URL https://www.planthealthaustralia.com.au/industries/pineapples/ (accessed 5.23.21).

Reinhardt, D.H., Uriza, D., Soler, A., Sanewski, G., Rabie, E.C., 2019. Limitations for pineapple production and commercialization and international research towards solutions. Acta Hortic. 1239, 51–64. https://doi.org/10.17660/ActaHortic.2019.1239.7

Sanewski, G., Bartholomew, D.P., Paull, R.E. (Eds.), 2018. The pineapple: botany, production and uses, 2nd Editio. ed, The pineapple: botany, production and uses. Boston, MA. https://doi.org/10.1079/9781786393302.0000

Yu, B., Ciesiolka, C.A.A., Rose, C.W., Coughlan, K.J., 2000a. A validation test of WEPP to predict runoff and soil loss from a pineapple farm on a sandy soil in subtropical Queensland, Australia. Aust. J. Soil Res. 38, 537–554. https://doi.org/10.1071/SR99104

Yu, B., Rose, C.W., Ciesiolka, C.C.A., Cakurs, U., 2000b. The relationship between runoff rate and lag time and the effects of surface treatments at the plot scale. Hydrol. Sci. J. 45, 709–726. https://doi.org/10.1080/02626660009492372

Knowledge gaps identified

Australian Research Data Commons, 2021. Australian Research Data Commons [WWW Document]. URL https://ardc.edu.au/resources/aboutdata/fair-data/ (accessed 5.3.21).

Conclusions and recommendations

Wyborn, C., Louder, E., Harrison, J., Montambault J., Montana J., Ryan, M., Bednarek, A., Nesshöver, C., Pullin, A., Reed, M., Dellecker, E., Kramer, J., Boyd, J., Dellecker, A., Hutton, J., 2018. Understanding the Impacts of Research Synthesis. Environmental Science and Policy. 86, 72–84. https://doi.org/10.1016/j.envsci.2018.04.013

Appendix 1. Australian Land Use and Management (ALUM) classifications by NRM region to commodity level

		Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Total	
		ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
3 Production from Dryland Agriculture and Plantation															
3.3.0	**Cropping**	63724	1.14	513942	3.27	-	-	40407	0.29	348	0.02	4960	0.12	623380	1.46
3.3.1	Cereals	1021	0.02	42072	0.27	-	-	89725	0.64	-	-	-	-	132818	0.31
3.3.2	Beverage and Spice crops	11	0.00	-	-	-	-	-	-	488	0.02	-	-	499	0.00
3.3.3	Hay and silage	177	0.00	1634	0.01	-	-	2021	0.01	-	-	269	0.01	4101	0.01
3.3.4	Oilseeds	800	0.01	-	-	-	-	-	-	3	0.00	-	-	803	0.00
3.3.5	Sugar	-	-	-	-	-	-	-	-	158272	7.12	-	-	158272	0.37
3.3.6	Cotton	-	-	1109	0.01	-	-	525	0.00	-	-	-	-	1634	0.00
3.3.7	alkaloid poppies	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.3.8	Pulses	-	-	1034	0.01	-	-	-	-	-	-	-	-	1034	0.00
3.4.0	**Perennial horticulture**	482	0.01	16	0.00	109	0.01	19	0.00	52	0.00	114	0.00	792	0.00
3.4.1	Tree Fruits	246	0.00	8	0.00	-	-	5	0.00	10	0.00	62	0.00	331	0.00
3.4.2	Olives	170	0.00	5	0.00	-	-	-	-	-	-	-	-	174	0.00
3.4.3	Tree nuts	141	0.00	-	-	-	-	-	-	-	-	-	-	141	0.00
3.4.4	Vine fruits	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.4.5	Shrub berries and fruits	13	0.00	-	-	-	-	-	-	-	-	-	-	13	0.00
3.4.6	Perennial flowers and bulbs	3	0.00	-	-	-	-	-	-	-	-	-	-	3	0.00
3.4.7	Perennial vegetables and herbs	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.4.8	Citrus	26	0.00	-	-	-	-	-	-	-	-	-	-	26	0.00
3.4.9	Grapes	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.5.0	**Seasonal horticulture**	5	0.00	-	-	-	-	-	-	6	0.00	33	0.00	44	0.00
3.5.1	Seasonal fruits	-	-	-	-	-	-	-	-	-	-	-	-	-	-

		Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Total	
3.5.2	Seasonal flowers and bulbs	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.5.3	Seasonal vegetables and herbs	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 Production from Irrigated Agriculture and Plantation															
4.3.0	**Irrigated Cropping**	37515	0.67	57214	0.36	193	0.02	3112	0.02	6552	0.29	809	0.02	105394	0.25
4.3.1	Irrigated Cereals	294	0.01	-	-	-	-	989	0.01	1418	0.06	-	-	2701	0.01
4.3.2	Irrigated Beverage and Spice crops	259	0.00	-	-	18	0.00	-	-	172	0.01	-	-	449	0.00
4.3.3	Irrigated Hay and silage	275	0.00	54	0.00	413	0.04	1466	0.01	280	0.01	-	-	2488	0.01
4.3.4	Irrigated Oilseeds	239	0.00	44	0.00	-	-	-	-	28	0.00	-	-	311	0.00
4.3.5	Irrigated Sugar	67261	1.20	2250	0.01	152281	16.26	104930	0.74	30089	1.35	-	-	356810	0.83
4.3.6	Irrigated Cotton	-	-	35840	0.23	-	-	2650	0.02	-	-	-	-	38490	0.09
4.3.7	Irrigated alkaloid poppies	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4.3.8	Irrigated Pulses	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4.3.9	Irrigated rice	-	-	-	-	-	-	6	0.00	-	-	-	-	6	0.00
4.4.0	**Irrigated Perennial Horticulture**	1145	0.02	350	0.00	109	0.01	197	0.00	699	0.03	3	0.00	2504	0.01
4.4.1	Irrigated Tree Fruits	5669	0.10	1256	0.01	309	0.03	4111	0.03	19567	0.88	461	0.01	31373	0.07
	Avocados	3801	0.07	24	0.00	-	-	17	0.00	1061	0.05	-	-	4903	0.01
	Bananas	64	0.00	117	0.00	18	0.00	-	-	14553	0.65	-	-	14752	0.03
	Mangos	1108	0.02	906	0.01	183	0.02	3633	0.03	918	0.04	-	-	6747	0.02
4.4.2	Irrigated Olives	197	0.00	2	0.00	-	-	4	0.00	-	-	-	-	203	0.00
4.4.3	Irrigated Tree nuts	11243	0.20	500	0.00	145	0.02	-	-	95	0.00	-	-	11983	0.03
	Macadamias	10760	0.19	500	0.00	145	0.02	-	-	76	0.00	-	-	11481	0.03
4.4.4	Irrigated Vine fruits	400	0.01	2	0.00	-	-	-	-	98	0.00	-	-	500	0.00
4.4.5	Irrigated Shrub berries and fruits	1441	0.03	1068	0.01	8	0.00	425	0.00	60	0.00	-	-	3001	0.01
	Pineapples	854	0.02	1068	0.01	-	-	113	0.00	-	-	-	-	2034	0.00
4.4.6	Irrigated Perennial flowers and bulbs	4	0.00	-	-	-	-	-	-	-	-	-	-	4	0.00
4.4.7	Irrigated Perennial vegetables and herbs	41	0.00	-	-	-	-	-	-	-	-	-	-	41	0.00
4.4.8	Irrigated Citrus	4353	0.08	1535	0.01	0	0.00	27	0.00	-	-	-	-	5914	0.01

		Burnett Mary		Fitzroy		Mackay Whitsunday		Burdekin		Wet Tropics		Cape York		Total	
4.4.9	Irrigated Grapes	518	0.01	1366	0.01	-	-	32	0.00	-	-	-	-	1916	0.00
4.5.0	**Irrigated Seasonal Horticulture**	6256	0.11	724	0.00	236	0.03	7954	0.06	561	0.03	-	-	15731	0.04
4.5.1	Irrigated Seasonal fruits	218	0.00	-	-	-	-	296	0.00	-		-	-	515	0.00
4.5.2	Irrigated Seasonal flowers and bulbs	38	0.00	-	-	-	-	-		7	0.00	-	-	45	0.00
4.5.3	Irrigated Seasonal vegetables and herbs	2475	0.04	-	-	578	0.06	4278	0.03	505	0.02	-	-	7836	0.02
4.5.4	Irrigated turf farming	239	0.00	74	0.00	99	0.01	250	0.00	88	0.00	-	-	750	0.00

Classifications which are bold and underlined are primary classifications. Classification classes which are bold are secondary classifications. Commodities are listed in italics. All other classifications are tertiary. Values for commodities are already included in the tertiary class which they are listed beneath. Values for tertiary classifications are not included in the values for secondary classifications. Secondary classifications consist of data that was not further classified to the tertiary level. (QLUMP 2019).

Appendix 2: Study sites with reported water quality impacts measured under field or experimental conditions, according to commodity type and Natural Resource Management region in the Great Barrier Reef catchment.

Commodity	NRM region	Location	Soil type	Years	Type	Measured	Publication
Vegetables	Burnett Mary	Alloway	Chromosol or Dermosol	2010-2011	Field	S, N, R, D	Nachimuthu et al. 2017
Vegetables	Burnett Mary	NR	Dermosol	2005-2007	Field	D	Stork et al. 2007
Cotton	Fitzroy	Emerald	Vertosol	2001-2003	Field	S, N, P, R, D	McHugh et al. 2008
Cotton	Fitzroy	Emerald (Denaro & Roberts farms)	Vertosol	1986-1987	Field	S, R	Carroll et al. 1995
				NR	Rainfall Simulator	S, R	Silburn and Glanville, 2002
				NR	Rainfall Simulator	P, R	Silburn et al. 2002
				NR	Modelling	S, R	Connolly et al. 1998, 1999, 2001
				1994-1996	Field	P, S, R	Simpson et al. 1998
Cotton	Fitzroy	Multiple	Multiple	1994-1996	Field	S, N, P	Noble et al. 1996
Cotton	Fitzroy	Emerald (multiple)	NR	1997-1999	Field	S, N, P, R	Waters 2001
Cotton	Fitzroy	Emerald (Elsden farm)	Vertosol	1996-1999	Field	S, R	Hulugalle et al. 2002; Yule & Rohde 1996; Rohde & Yule 1995

Commodity	NRM region	Location	Soil type	Years	Type	Measured	Publication
Cereals/pulses	Fitzroy	Emerald (Elsden farm)	Vertosol	1996-1999	Field	S,R	Hulugalle et al. 2002; Yule & Rohde 1996; Rohde & Yule 1995
Cereals/pulses	Burdekin	Kilcummin	Vertosol	1992	Rainfall Simulator	R	Freebairn et al. 1992
Cereals/pulses	Fitzroy	Wolfgang	Vertosol	1992	Rainfall Simulator	R	Freebairn et al. 1992
Cereals/pulses	Fitzroy	Retro	Vertosol	1992	Rainfall Simulator	R	Freebairn et al. 1992
Cereals/pulses	Fitzroy	Orion	NR	1992	Rainfall Simulator	R	Freebairn et al. 1992
Cereals/pulses	Fitzroy	Capella	Vertosol	1983-1993	Field	S, N, P, R	Carrol et al.1997
Cereals/pulses	Fitzroy	Capella (Godonstone catchment)	Vertosol	1999-2018	Field	S, N, P, R	Rogusz 2019; Rogusz & Burger 2017; Rogusz et al. 2012; Murphy et al. 2013
Cereals/pulses	Fitzroy	Brigalow Research Station	Sodosol	1982-current	Field, Modelling	S, N, P, R, D	Radford et al. 1991; Thornton & Yu 2016; Elledge & Thornton 2017; Silburn et al. 2009; Thornton et al. 2007; Cowie et al. 2007
Cereals/pulses	Wet Tropics	Kairi Research Station	Ferrosol	1998-2001	Field, Modelling	S, N, R, D	Cogle et al. 2011
Macadamia	Burnett Mary	Bundaberg	Kandosol	2005-2006	Field	S, N, P, R	Stork et al. 2007, 2009, 2012
Banana	Bundaberg	Windermere	Ferrosol	2011-2014	Field	N, P, D	Bhattarai and Midmore 2015
Banana	Wet Tropics	South Johnston	Dermosol	1995–1997	Field	N, D	Armour et al. 2013
Banana	Wet Tropics	Tully–Murray	Dermosol	2004-2005	Field	N, D	Wakelin et al. 2011
Banana	Wet Tropics	North Johnston	Krasnozems	1996-1999	Field	S, N, R	McKergow et al. 2004a; McKergow et al. 2004b

Commodity	NRM region	Location	Soil type	Years	Type	Measured	Publication
Banana	Wet Tropics	Tully–Murray Rivers and Granite Creek	NR	2002-2003	Field	S, N	Faithful and Finlayson 2005
Banana	Wet Tropics	Johnstone River system	Ferrosol, dermosols kandosols	1991-1996	Field, Modelling	S, N	Hunter and Walton 2008
Banana	Wet Tropics	Tully–Murray	NR	2005-2007	Field	S, N, P	Bainbridge et al. 2009
Banana	Wet Tropics	DAF Research Station South Johnstone	Dermosol	2010-2015	Field	N, P, D, R	Masters et al, 2017; Armour et al. 2012
Banana	Wet Tropics	Tully River Catchment	Dermosol	2004-2006	Field	N, D	Rasiah et al. 2010
Banana	Wet Tropics	Johnstone River Catchment	Ferrosol	NR	Field	N	Rasiah and Armour 2001
Pineapple	Burnett Mary	Yandaran	NR	2019-2020	Field	S, N, P	Australian Pineapples 2019b, 2019a; Griffin 2020b, 2020a.
Pineapple	Burnett Mary	Imbil	Sandy Loam	1988-1991; 1995-1996	Field	S, R	Ciesiolka et al. 1995; Coughlan and Rose 1997; Palis et al. 1997
Pineapple	Burnett Mary	Goomboorian	Loamy Sand	1991-1995	Field	S, R, N	Coughlan and Rose 1997; Yu et al. 2000b, 2000a

NR - Not recorded; S - Sediment; N - Nutrients; P - Pesticides; R - Runoff quantity; D - Deep drainage. No study sites were located for Avocado.