Understanding the economics of horticultural management practices and systems for improving water quality runoff in the Great Barrier Reef catchment areas

Reef Plan Action 2.4: Gap Analysis Report

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Executive Summary

The main objective of this report is to identify available studies and prioritise future economic research on dominant horticultural cropping systems in the Great Barrier Reef (GBR) catchment. Due to the wide array of horticultural crops and production systems, available databases have been utilised to identify the major crops by area that pose the highest potential risk to reef water quality (RWQ)[1] impact and decline. However, it is anticipated based on preliminary agronomic research that different horticultural production systems are likely to have different effects on both runoff and sub-surface leachate. Crops are therefore grouped according to common production system attributes. This allows for possible transfer extension of research findings to other horticultural crops within each group.

Of the 150 different horticultural crops grown in the GBR catchment, thirteen major horticultural crops have been identified for this report. Only crops exceeding 1,000 hectares (ha) in total within the catchment are considered (excluding banana plantations and intensive horticulture, sometimes referred to as protected cropping)[2]. These include six perennial crops (macadamias, mangoes, avocados, citrus, pineapples and grapes), six vegetable crops (beans, sweetcorn, potatoes, capsicums, tomatoes and pumpkins) and one seasonal fruit crop (melons). A literature review was conducted on each of these crops to identify published studies that evaluated the economic cost-benefit of RWQ decline risk reduction practices.

The report and findings align with practices listed in the Horticulture Water Quality Risk Framework (2017-2022) as developed by the Paddock to Reef (P2R) Team and Growcom. Despite a relatively small land use area, horticulture is acknowledged in general to involve some of the most intensive farming practices in agriculture. This has implications for risk of RWQ decline. The Soil Catchment and Riverine Processes Group (2022) has compiled much of the background research investigating horticultural crops in the GBR catchment, and where applicable, their potential impact on the Reef (RP240 'Improving knowledge and research for horticulture and cropping activities'). In complement to their body of work this literature review focusses on practices that reduce the risk of excess sediment, nitrogen and chemical residues reaching the GBR and identify any economic related horticulture specific findings.

The findings conclude there is limited publications available that assess RWQ risks from the horticulture industry, and none that thoroughly demonstrate an economically viable improved management practice for the industry. Positively, horticultural practices are generally progressive due to market requirements (e.g., food safety requirements) and constraining production factors (e.g., nutrient and produce quality linkages). Because of these factors, horticulture leads the agricultural industry in several alternative fields in terms of innovation and demonstration of best practice. Strategic investment in research, industry development and extension which utilises such innovation

[1] Note: RWQ is not a recognised or official acronym for reef water quality, but is merely used here due to the frequency of occurrence throughout this analysis.
[2] Bananas have been excluded as they have an existing Reef Water Quality Risk Framework (2017-2022). Protected cropping is excluded as it tends to have more permanent structures, with a very different set of risks compared to traditional extensive horticulture (i.e. crops grown in substrate media or under protection are likely to result in less soil related disturbances).

and momentum for practice change may well deliver more rapid outcomes for improved RWQ from the horticultural sector.

Future research priorities incorporating economic analysis include those crops with the highest potential RWQ impact. These may include new macadamia plantations, avocados and pineapples. Others for considerations could be mulched crops (due to environmental management requirements of micro-plastic pollution) and the intensive cycling of continuous supply root crops such as sweetpotatoes which pose persistent risks of RWQ decline regardless of season.

Abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ACLUMP	Australian Collaborative Land Use and Management Program
ALUM (V8)	Australian Land Use Mapping (Version 8)
ATCM	Australian Tree Crop Map
BMP	Best Management Practice
DAF	Department of Agriculture and Fisheries
DES	Department of Environment and Science
DIN	Dissolved Inorganic Nitrogen
GBR	Great Barrier Reef
GPS	Global Positioning System
GVP	Gross Value of Production
Ha	Hectare
IPM	Integrated Pest Management
N	Nitrogen
NRM	Natural Resource Management
NUE	Nitrogen Use Efficiency
OGBR	Office of the Great Barrier Reef
P	Phosphorus
P2R	Paddock to Reef
QLUMP	Queensland Land Use Mapping Program
R	Residue
RSE	Relative standard error
R&D	Research and Development
RWQ	Reef Water Quality
SCS	Scientific Consensus Statement
SA	Statistical Area
SEQ	South East Queensland
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
WQIP	Water Quality Improvement Plan

1 Introduction

Agricultural practices in Great Barrier Reef (GBR) catchment areas have been identified as contributing to downstream pollutants that impact the health of the reef ecosystem. The main concerns from cropping activities are those that result in farm inputs and sediment making their way to the GBR, either in runoff water, or via sub-surface drainage. The Scientific Consensus Statement (SCS) 2017 concludes that nutrients (particularly nitrogen and phosphorous), fine sediments and pesticides pose a water quality risk to the GBR, with agriculture recognised as an important contributor (Waterhouse, et al., 2017). In addition, the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) identifies plastics (particularly micro plastics) as an emerging threat to the Reef; while irrigation practices and water use efficiency, linked to nutrient deep drainage and surface runoff risks, are identified for validation in the Reef 2050 Water Quality Research Development and Innovation Strategy (2017-2022), (Australian and Queensland Governments, 2018a)**.**

As an area of focus, the SCS identifies horticulture as a cost-effective opportunity for improving reef water quality (RWQ) where activities include pesticide and nutrient application, and the exposure of soil to potential erosion. Despite a small footprint (approximately 0.17% of catchment area), horticulture is likely to be more environmentally impactful per area grown, with crop characteristics and consumer expectations on product quality requiring more intensive inputs and operations. However, horticulture presents as a complex agricultural category given it is comprised of a diverse cropping mix. These range from perennial tree orchards to short term seasonal crops, as well as plantation crops such as pineapples, flowers, turf and even crops grown in soil-less media under glasshouse.

1.1 Report objectives and aims

The main objective of the report is to provide direction for future economic work in the Reef 2050 WQIP relating to horticultural cropping systems. This will enable further delivery on Action 2.4 of the Reef Action Plan (Australian and Queensland Governments, 2018b, p. 31):

> "Identify and address barriers to change and practice improvement uptake through programs and policy" – "Conduct economic evaluations to validate the economics of management practices that improve water quality and provide information to landholders as part of the extension program."

Source: Reef 2050 WQIP 2017-2022 (reefplan.qld.gov.au)

The Independent Science Panel (ISP) of the SCS also states that "further consideration of economic and social dimensions is needed in the development and implementation of programs to improve reef water quality" (Waterhouse, et al., 2017, p. 8). Given the potential for better farm management practices to improve runoff water quality, it is important to determine not only environmental outcomes but also the economic impact on the horticultural sector. This is expected to influence the likely adoption of improved practices by farmers and will also give direction to policy makers where adoption levels are expected to be low (i.e., where economic outcomes are negative).

This report aims to:

- Prioritise the horticulture commodities that contribute the largest losses of nutrients, sediments and pesticide by area within the GBR catchment.

- Identify key production system similarities (categories) for the future application of more general RWQ improvement solutions.
- Identify gaps in the economics of horticultural management practice changes (by category) relating to RWQ impacts.
- Prioritise areas of focus for future economic analysis.

1.2 Scope and approach

Due to the lack of homogeneity across horticultural production systems, it is important to focus on those having the biggest overall impact on RWQ. Due to the lack of data available on individual crop contributions, this is achieved via analysis of the dominant cropping areas within the GBR catchments. Although this assumes impacts are directly proportional to area, it is likely that cropping system differences would also influence overall impacts and should be considered in future crop selection processes when such information is available (noted as a future research priority).

The review of past economic studies is limited to those crops identified in the selection process, however, in certain cases recommendations could be extrapolated to those under similar production systems. The following sections include crop selection and production system grouping methodologies.

1.2.1 Crop Selection Methodology

Categorisation:

The Australian Land Use and Management Classification Version 8 (ALUM (V8)) classified land use as a three-tiered hierarchical structure (primary, secondary and tertiary classes).

> Five primary classes are identified according to levels of intervention or potential impact on the natural landscape. Water (e.g., dams, lakes, etc.) is included separately as a sixth primary class. Primary and secondary levels relate to the principal land use, while tertiary classes may include additional information on commodity groups, specific commodities, land management practices or vegetation information.

Source: (Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), 2019)

Horticulture fits within these three categories of the ALUM (V8) primary classes, Level 3 (dryland agriculture), Level 4 (irrigated agriculture) and Level 5 (Intensive horticulture, sometimes referred to as protective cropping). Within these broad categories, there are secondary and tertiary divisions. For horticulture, the secondary division is grouped as perennial (defined as plants living more than 2 years) and seasonal horticulture (less than 2 years) for the extensive crops. Production systems from Dryland and Irrigated Agriculture that include horticultural crops (classes 3.4, 3.5, 4.4, 4.5 and 5.1) are listed in Table 1. The tertiary division is also important for horticulture, as it further divides the groups into categories with similar characteristics (see Table 1).

Table 1: Primary, Secondary and Tertiary Australian Land Use and Management Classification Version 8 (October 2016) classes included in the scope of this report.

3	***Dryland Agriculture and Plantations***	***4***	***Irrigated Agriculture and Plantations***	***5***	***Intensive Uses***
3.4	**Perennial horticulture**	**4.4**	**Irrigated Perennial horticulture**	**5.1**	**Intensive horticulture***
3.4.1	Tree Fruits (including bananas*)	4.4.1	Irrigated Tree Fruits (including bananas*)	5.1.1	Production nurseries*
3.4.2	Olives	4.4.2	Irrigated Olives	5.1.2	Shadehouse*
3.4.3	Tree nuts	4.4.3	Irrigated Tree nuts	5.1.3	Glasshouses*
3.4.4	Vine fruits	4.4.4	Irrigated Vine fruits	5.1.4	Glasshouses: hydroponic*
3.4.5	Shrub berries and fruits	4.4.5	Irrigated Shrub berries and fruits	5.1.5	Abandoned intensive Horticulture*
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	**Seasonal horticulture**	**4.5**	**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		

Note:
* Crop classifications that are excluded from the scope of the report.

For the purposes of this report, there are two sets of horticultural crops that are excluded from the scope. The first is bananas, as it has its own Reef Water Quality Risk Framework (Australian and Queensland Governments, 2020a). Tree fruits are separated into “Bananas” (out of scope) and “Tree fruits excluding Bananas” (in scope). Level 5 crops are the second exclusion (intensive horticulture, otherwise known as protected cropping). These tend to be more permanent structures, with a very different set of risks compared to traditional extensive horticulture (i.e., crops grown in substrate media or under protection are likely to result in less soil related disturbances).

The majority of agricultural crops (in terms of area) are grouped into the “Cropping” category 3.3 and 4.3 (e.g., cereals, beverage and spice crops, hay and silage, oilseeds, sugar, cotton, alkaloid poppies, pulses)[3] that is not included in Table 1. Horticulture then provides (arguably) a default category for the remaining crops (and even this categorisation may still be contentious, with some crops such as ginger and alkaloid poppies not included in horticulture despite sharing many of the attributes of a

[3] Production from dryland and irrigated agriculture and plantations that do not include horticulture (most of Classes 3 and 4) are included in Appendix A for reference to help understand where horticulture fits within the total classification. Note: Other intensive land uses (excluding horticulture) are not displayed in this report (Classes 5.2 to 5.9).

horticultural crop).[4] The complete list of over 150 horticultural crops is attached as Appendix B. Many of these are not grown in the reef catchment area, or only cover small areas due to domestic market limitations and/or a high cost of production restricting exports. These are not included in the scope of the literature review due to their limited impact on the Reef. While some of these crops could pose significant localised threats to RWQ, due to complex crop requirements and management practices, the overall impact is largely determined by the total area contribution of a crop.

1.2.2 Area Selection Methodology

The regions and crop locations reviewed are limited to catchments whose runoff water have the highest potential to reach the GBR, i.e., the eastern catchment areas of Queensland located adjacent to the Reef. These are listed as follows:

- The Burnett Mary Natural Resource Management (NRM) area
- The Fitzroy NRM area
- The Mackay Whitsunday NRM area
- The Burdekin NRM area (sometimes referred to as the Dry Tropics)
- The Wet Tropics (also called Terrain) NRM area; and
- Cape York (note this refers only to the part of the NRM area which drains to the east).

The area of the GBR catchment covers approximately 42 million ha depending on the data source. For purposes of this report, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) data is used as a summation of Classes 1 to 6 according to ALUM (V8), the same data utilised to investigate the respective crop areas. An exception is Cape York which includes the entire peninsular. For this, an area of 4.3 million ha is applied as defined by the total area of the seven (7) drainage basin areas as presented in the Reef 2050 WQIP (Australian and Queensland Governments, 2020b).

This makes a total estimated catchment area of 42.8 million ha considered for the review (see Appendix C for different measurements of reef catchment area). While the variations are imperfect, it does not have a large impact on the overall conclusions of the crop selection analysis. A complication in dealing with data from different sources arises from the lack of alignment over geographical areas. For example, the exact physical catchment does not match the NRM boundary, and the Australian Bureau of Statistics (ABS) Statistical Areas SA2 and SA4 boundaries do not match either in multiple instances. However, for the purpose of this report, that fine detail is unlikely to change the outcomes.

The positioning and relative size of the six catchments are shown in the map below (Figure 1), with the names of the 35 river basins included. The major horticultural areas are circled in red on the map, but are not drawn to scale and are for indicative purposes only.

[4] Two clarifying notes in terms of terminology are: “Lifestyle horticulture” is an official grouping determined by the Australian Bureau of Statistics (ABS), including nurseries, cut flowers and turf. This transects several categories but is not based on them having similar Reef Water Quality (RWQ) risks. For the purposes of this report, part of this category is also excluded where nurseries and several flowers are considered intensive, while irrigated turf is in scope. The risks associated with the other crops are dealt with by grouping them appropriately as per ALUM classifications.
Secondly the phrase “protected cropping” usually refers to intensive horticulture (5.1).

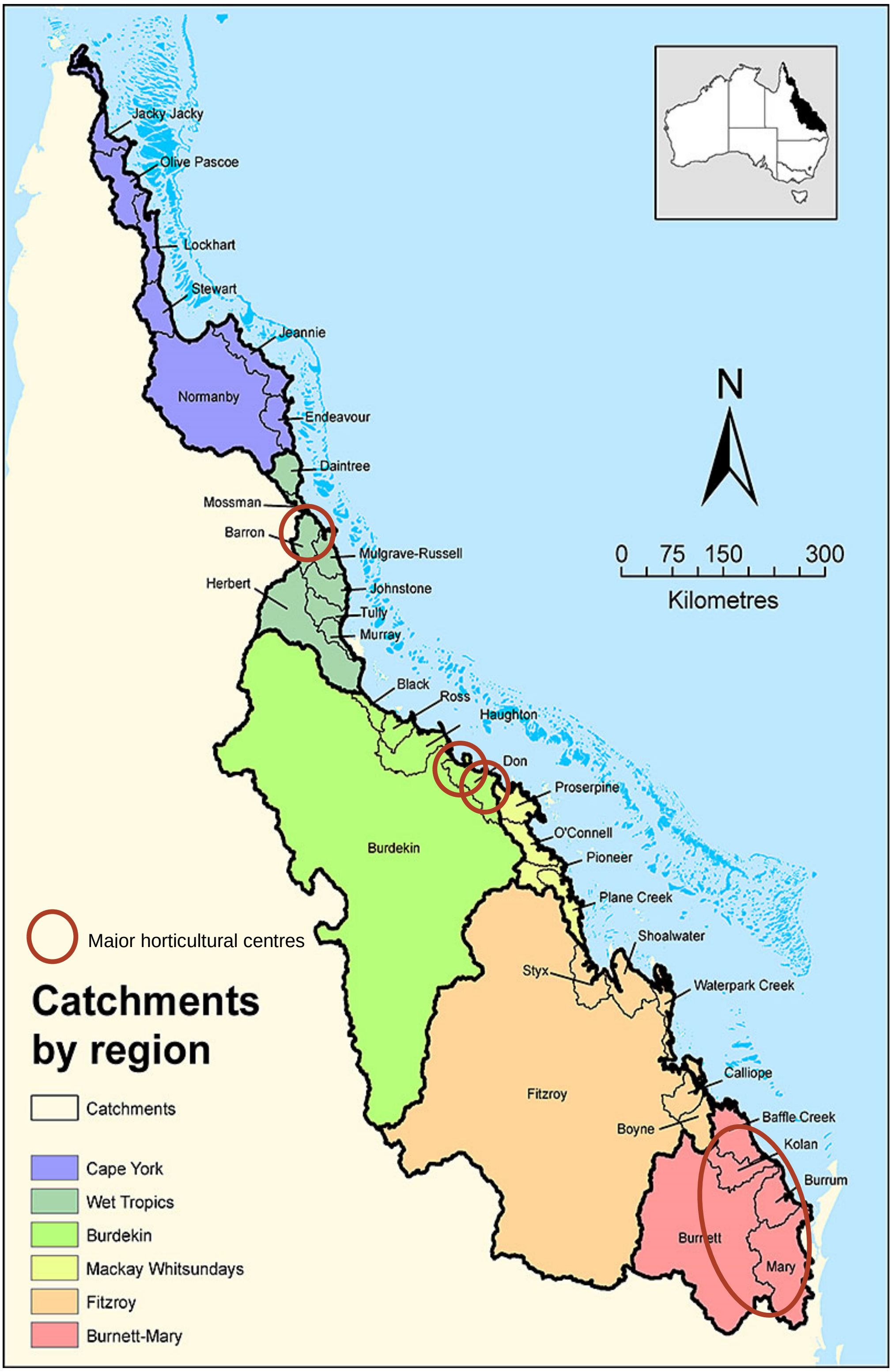

Figure 1: Map of Great Barrier Reef catchment and major horticultural centres

Source: Australian and Queensland Governments (2019).

While the Burdekin and Fitzroy are the largest reef catchment areas, the Burnett Mary has the biggest concentration of horticultural production, containing 56% (32,729 ha) of the GBR catchment's horticultural cropping area (excluding bananas and intensive cropping). While this is centred around Bundaberg and Childers, there is an array of horticultural cropping taking place along the eastern length of GBR catchment area. The Burdekin follows second with 14,447 ha (25% of the horticultural area), having its cropping largely located around the Bowen-Gumlu area. Although the Wet Tropics has over 10,000 ha of banana land, being out of scope for this study, the overall contribution to the remaining GBR horticulture land area drops to 12% (6,832 ha), centred largely around the Atherton Tablelands. While the Fitzroy is the largest NRM (accounting for over 36% of the total land area), its horticultural contribution is relatively small at 6% (3,591 ha). The last two NRMs (Mackay Whitsunday and Cape York) have much lower horticultural contributions at <1% (358 ha and 140 ha, respectively. The final selection criterion includes any horticultural crops exceeding 1,000 ha within the GBR catchment.

1.2.3 Literature Search Methodology

Identifying relevant literature involved a Scopus search, a Google Scholar search, and discussions with various industry associations. There was also significant guidance taken from the RP240 Project: 'Improving knowledge and research for horticulture and cropping activities', (Soil Catchment and Riverine Processes Group, 2022) where various past studies with an agronomic focus had already been identified. A more detailed search engine procedure is included in Appendix D.

Based on the SCS, searches included practice change references relating to soil, pesticide, nutrient and water management. The search was also limited to selected crops and focussed on:

- individual crop impacts in terms of RWQ
- management practice change and their impact on RWQ
- the economic impact of management practice change (e.g., identifying the most profitable practice aligned with improved water quality outcomes).

The following sections identify the most impactful (by area) horticultural cropping systems in the GBR catchment. This includes details on the data sources, areas per crop and a basic crop overview. Crops are also grouped according to production system commonalities.

2 Crop Selection

The challenge of crop selection remains simplifying a category with over 150 different crops, ranging from perennial crops to seasonal herbs and vegetables grown over short time periods (e.g., 5 weeks for coriander). It includes crops harvested for their leaves, roots, fruits, berries, nuts or even the entire plant (as in the case of irrigated turf and some leafy vegetables and herbs), with shelf-life ranging from a few days to over a year (in storage). This requires a wide range of production systems likely to differ significantly in risk of impacting water quality decline.

Perennial horticultural areas are more easily estimated when compared to seasonal horticulture that often has a very short growing window (with plantings more sensitive to market and weather conditions than longer-cycle crops). Seasonal crops are also often rotated, so the same land area can be host to three or more different crops in a year. Given significant fluctuations in land area under production and often old data substantiating such change, it is difficult to access accurate area records for the vast array of crops from year-to-year, particularly when there are multiple data sources with different classification levels, ages and forms of data available.

2.1 Data Sources

There are several data sources that list growing areas for different crops. These can often be inconsistent which makes consideration of all data sources in the crop selection process important.

The main official estimates for area under horticulture comes from Australian Collaborative Land Use Mapping and Management (ACLUMP) which coordinates land use mapping in Australia to ensure consistent coverage at both ‘national’ and ‘catchment’ scale. Catchment scale land use mapping is more detailed when compared to national scale mapping and is produced by combining state cadastre, public land databases, fine-scale satellite data, other land cover and use data, and information collected in the field. Land use is divided into each of the Australian Land Use and Management (ALUM) categories. When the tertiary level is unclear or changing, the secondary level becomes the default (ABARES, 2021).

ABARES uses ACLUMP data separated in the NRM catchments and allocates area according to ALUM (V8) categories, down to tertiary level where possible. See Appendix E for the complete list of crop areas per catchment. This dataset ranging from 2008 to 2019 quantifies the horticultural areas as 58,760 ha perennial, 24,765 ha seasonal and 729 ha intensive, giving 84,254 ha total (including bananas and intensive horticulture). This makes it a useful database, even though there are substantial areas limited to secondary classification (15,688 ha to 4.5 alone, and 18,944 ha in total). However, it does give a structured breakdown of the perennial crops into the different commodities in general.

Most of the data contained in ACLUMP is originally derived from Queensland Land Use Mapping Program (QLUMP) data (see below) (ABARES, 2021). QLUMP has data for each separate NRM (collected at different times / years from 2013 to 2017) (Queensland Government, 2020). This data is generally limited to secondary classifications (dryland and irrigated perennial and seasonal horticulture), with the combined total being 84,193 ha (58,500 ha perennial, 24,765 ha seasonal, 728 ha intensive) making it almost identical to the ABARES data. Some of the major commodities are included at a tertiary level, but not consistently across NRMs for each commodity. The QLUMP data, comes from several updates which include:

- Fitzroy and Burnett Mary NRM regions (land use updated for 2017)
- Mackay Whitsunday and Burdekin NRM regions (updated in 2016)
- Wet Tropics (updated from 2015) and
- Cape York in Far North Queensland (land use mapping to 2013).

Note that Cape York includes the entire region, not just the GBR catchment areas to the East, and its area of horticultural cropping was insignificant (under 1,000 ha and mainly bananas).

Australian Bureau of Statistics (ABS) data is very different and sourced from sample surveys annually and updated more extensively every 5 years with census results. The area is based on responses relating to business activity, for those agricultural operations with an estimated value of over $40,000 /

year. It does not follow ALUM categorisation and divides horticultural crops into three categories: fruit and nuts; lifestyle horticulture (nurseries, cut flowers and cultivated turf); and vegetables. This makes it difficult to align with ABARES figures below as lifestyle horticulture transects all three primary ALUM categories. The horticultural area in 2020/21 survey was estimated to be 69,716 ha (including out of scope categories). See Appendix F for more detail. Source: (ABS, 2022a).

There are some more refined area updates, particularly with regard to perennial crops, where the National Tree Crop Project has been updating the ACLUMP figures via the Australian Tree Crop Map (ATCM) Dashboard showing location and extent of all commercial horticulture tree crops, including: avocado, banana, citrus, macadamia, mango, and olives (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 and ‘ground-truthed’ (including with online submissions). Data was updated in December 2021, and shows an increased area planted to macadamia and avocados.

While it is difficult to determine how much of the change in newly planted land was coming from either sugar cane, horticultural or other cropping land, these more recent figures ATCM have been used, with the acknowledgement that this may introduce inconsistencies in data reconciliation with ABS and ABARES data. Where more detailed area definition is required within an ALUM sub-class, the ABS data is used, but the general ALUM classification has been retained where possible.

2.2 Crop Short-list

Assuming a larger crop footprint is normally directly correlated with potential impact, the crops that are considered in the review are those that exceed an area of 1,000 ha within the GBR catchment (see Table 2). Appendix E also shows a full breakdown of cropping areas per NRM region. Although the review focuses on dominant crops, it should be noted that some crop exclusions share many characteristics with those considered in the review to which research findings could be extended.

In terms of ABS data, the survey of economic data supported by the census every 5 years is based on a turnover exceeding $40,000 per annum. This would include multiple crops grown on the same area within the same year. However, spatial data from ABARES allocates land area at a specific point in time. This likely contributes to inconsistencies for horticultural crops due the short growing window for several seasonal crops and where multiple crops area grown in the same year. Although this makes it difficult to define exact areas grown to each seasonal crop, it is unlikely to change the outcome of the crops identified in Table 2. The contribution to Gross Value of Production (GVP) also confirms that all major crops within scope of the review have been included (see Appendix H) (ABS, 2022b).

Despite horticulture only representing about 7% of the land area from all cropping in Reef NRM’s (ABS, 2022a), it contributes approximately 58% to total GBR catchment crop Gross Value of Production (GVP). If livestock is added to cropping to get a figure for total agriculture, horticulture’s contribution is still 34% of total agriculture GVP (ABS, 2022b). Removing bananas and protected cropping reduces this to 41% of cropping (or 24% of total agriculture).

Table 2: Horticultural crops in GBR catchment exceeding 1,000 ha

ALUM Category	Description *	Crop	Area (ha) 2020/21	% of Hort in Scope	Data Source
3.4.1 & 4.4.1	Tree fruits	Avocados	6,576	11.3%	ATCM
		Mangoes	5,571	9.6%	ATCM
3.4.3 & 4.4.3	Tree nuts #	Macadamias	16,297	28.1%	ATCM
3.4.5 & 4.4.5	Shrub berries and fruits	Pineapples	2,391	4.1%	ABS^
3.4.8 & 4.4.8	Citrus	Citrus	5,769	9.9%	ATCM
3.4.9 & 4.4.9	Grapes	Grapes	1,156	2.0%	ABS
3.4 & 4.4	**Perennial Horticulture**	**6 selected**	**37,759**	**65.0%**	
3.5.2 & 4.5.2	Seasonal fruit	Melons	2,283	3.9%	ABS
3.5.3 & 4.5.3	Seasonal vegetables and herbs	Sweet corn	4,094	7.0%	ABS
		Beans	4,067	7.0%	ABS
		Potatoes	2,325	4.0%	ABS
		Capsicums	1,486	2.6%	ABS
		Tomatoes	1,198	2.1%	ABS
		Pumpkins	1,009	1.7%	ABS
3.5 & 4.5	**Seasonal Horticulture**	**7 selected**	**16,461**	**28.3%**	
Total Selected Horticultural Area		**13 selected**	**54,220**	**93.3%**	
Total Horticultural Area in scope			**58,097**	**100.0%**	**ABS**

Notes:
* Includes both dryland and irrigated crops.
# Australian Tree Crop Map (ATCM) 2021 estimates include most dominant tree crops[5], but not seasonal fruit and vegetables (Applied Agricultural Remote Sensing Centre, 2021).
^ABS figures were used for pineapples and the various vegetable[6] crops as ABARES figures do not adequately distinguish the areas for these individual crops from the overall respective categories.

Sources: ABS (2022a), Applied Agricultural Remote Sensing Centre (2021).

Compared to broadacre cropping (which includes hay, cereals, pulses, oilseeds, cotton and sugar cane), the GVP of horticulture in the GBR catchment NRM's is 31% larger from an area less than 10% in size, with the in-scope crops reported in this study being of similar value to all broadacre cropping (ABS, 2022a,b). This equates to nearly $34,000/ha for horticultural crops in the GBR catchment, (and $24,000/ha for in scope crops) versus an average of $2,328/ha for all other crops (according to ABS area figures) (ABS, 2022a,b). Between horticultural crops there are also large differences, e.g., the value of tomato production is nearly five times higher than pumpkins from a similar area grown. However, care should be taken in application of these figures with GVP and crop area datasets originating from surveys with in-depth analyses indicating discrepancies with the results (e.g., datasets suggest that pineapples are worth less than pumpkins per ha, despite the possibility of higher yields and prices).

[5] Compared to older ABARES and ABS data, the major change is in macadamias, increasing in area from 11,481 ha, and to a lesser extent, avocados (increasing from 4,903 ha). For the purposes of this study, the choice of dataset would not affect the scope of crops over 1,000 ha. See updated figures in Appendix G, which also shows the river basins that contain the most horticultural activity.
[6] Note: although the botanic definition of a fruit would include beans, sweet corn, capsicums, tomatoes and pumpkin (Merriam Webster, 2022), ALUM (V8) categorises them as seasonal vegetables, and nuts as tree nuts. ABS also includes melons with the vegetables.

To ensure crops included for review aligned with industry expectations, partners from Growcom, the Department of Agriculture and Fisheries (DAF), the Department of Environment and Science (DES), the Office of the Great Barrier Reef (OGBR) and industry representatives were consulted. There was consensus that despite challenges with the available data, the major crops had been considered.

2.3 Crop Overview

The following sections highlight some important attributes of the selected crops including information on growing locations due to market requirements and production system risks. Such information is important when considering the potential impact on RWQ and future research priorities where past research and literature may be lacking.

2.3.1 Selected crop information

2.3.1.1 Perennial crops

The general requirement of most orchards is that they are well drained. This is particularly important for both major crops in the catchment (avocados and macadamias are prone to attack from phytophthora and other root borne disease in wet soil). Prior to planting, the land is often prepared for long-term drainage after which the soil is loose, bare, and susceptible to erosion until adequate ground cover is established (required before young orchards have canopied). Due to inter-row drainage designs, there is a high risk of runoff following rain events which is exacerbated by vehicle compaction and steeper slopes.

Queensland macadamia areas have grown from 11,481 ha in 2011 to over 16,000 ha in 2021. This is expected to increase by approximately 2,000 ha/year[7] over the next few years (Burnett, 2022) increasing the potential for any runoff risks (and impact to RWQ) associated with this crop in the short to medium-term.

Avocados have also increased significantly from 4,903 ha in 2010 to 6,576 ha in 2022, but due to the current domestic over-supply and subsequent price falls, it is unlikely that there will be further large increases in plantings. Citrus and grapes tend to have more stable areas of production, and are grown further inland, with lower annual rainfall (and therefore lower risks) than coastal areas, although it is understood that investment in more recent irrigation technologies may be lagging in some citrus areas, resulting in potential leaching events.

2.3.1.2 Pineapples

Although pineapples are classified as perennial, some cultivars produce fruit and are terminated within 24 months (especially fresh market varieties). Even the preferred canning cultivar (Smooth Cayenne) is normally only grown for a plant crop and one ratoon, a little over 3 years in total. Traditionally Queensland had mainly produced pineapples for the Brisbane cannery, but this market has declined substantially with the demand for fresh pineapples increasing. Overall, the area grown to pineapples has been in long term decline, with the 2010 figure of 2,385 ha dropping to an estimated 1,184 ha in 2020 (Newett, 2022). The mix between fresh market and cannery areas are 553 ha of Smooth Cayenne and 629 ha of fresh market varieties. Urbanisation pressure and preferential growing conditions north of South East Queensland (SEQ) means there is currently a movement of

[7] 3,000 to 4,000 ha nationally, with much of this coming from Queensland.

the fresh market industry from its traditional SEQ footprint to locations further north in the GBR catchment.

Due to the distance from Brisbane, most canning crops are grown in the Burnett Mary catchment (and south-east Queensland), leaving almost the entire crop grown in the Fitzroy and northwards as fresh market varieties. Note, it is possible that fresh market varieties are grown an additional year for a second harvest, although this is not common due to small size fruit normally produced by ratoon crops. This means that pineapples have risks of impacting RWQ; and as not always meeting the definition or attributes of a perennial crop, are closely associated with the risks from seasonal horticulture, in particular seasonal vegetables. This is due to a lack of ground cover increasing the chance of erosion, rows often being planted north-south regardless of slope direction, requirements of residual herbicides and a high nutrient loading during crop establishment phase of vegetative material with little to no roots thereby increasing leaching risks.

2.3.1.3 Green beans and sweetcorn

In terms of area, green (french) beans and sweetcorn are the two major vegetable crops supplying a few different markets. Traditionally fresh market beans were hand-picked multiple times per planting with this continuing largely in the Gympie region (under limited area). Currently most beans (and sweetcorn) are grown by larger corporate farms (e.g., Mulgowie Farming Company, Rugby Farm, Kalfresh Vegetables) that often produce all year-round using different seasonal locations along the Australia eastern seaboard to exploit seasonality windows and ensure continuity of supply to major retailers. For example, production occurs in the warmer tropics over winter but moves further south over summer to avoid high temperatures that impact on bean quality. This is likely to reduce risks to RWQ in the wet tropics at times of highest rainfall.

Continuity of supply requires a regular planting program (weekly or even more frequently). The maturity window is very narrow (normally only a few days either side of the optimal harvest day). Regardless of the weather, it is important to plant and harvest on time to ensure smooth supply of fresh market beans, which may increase the risk to RWQ. However, the processing or frozen-produce markets are less sensitive to exact planting dates due to the extended product shelf-life which may allow for lower risks to RWQ arising from planting and harvesting operations.

Apart from beans and sweetcorn, there are a number of other smaller crops (e.g. cabbage, lettuce, broccoli, and some herbs) that are either machine or hand harvested to supply the market with produce that normally has a shelf-life of approximately one week, which result in similar risk considerations to RWQ risk considerations. Overall, these crops need to be visually flawless to get the best chance of achieving sales. Blemishes such as pest or disease marks downgrade the produce, so there is usually a strong scouting and repeated spray protection program on farm dependant on the crop, further adding to RWQ risks.

2.3.1.4 Tomatoes, capsicums and melons

Tomatoes, capsicums and melons are seasonal crops with higher-than-average values of production per hectare. They produce a large quantity of fruit in a short timeframe, which can be severely compromised by deficient nutrient levels. With fertiliser making up only 5-10% of overall production costs, there is little incentive to lower fertiliser rates where the impact on revenue and costs (per kilogram (kg) for expensive harvesting and packing labour) could be substantial.

Occasionally growers make double use of the existing inputs and grow a second (usually different) crop on the same plastic. While this may be with reduced fertiliser, it must be noted that with this and other crop rotations that occur within one season, the total fertiliser applied is the sum applied on each crop.

2.3.1.5 Sweetpotatoes

Root-harvested crops, such as potatoes, are likely to have a higher risk of sediment loss due to the harvesting process if exposed to high rainfall events (including sweetpotatoes which are technically not a potato but treated by ABS as such). Queensland potatoes are predominantly a winter grown crop, with harvest being in late spring which is outside of summer peak rainfall times. Sweetpotatoes are harvested and supplied to fresh markets continuously due to storage limitations (soft skinned), thus increasing the potential of topsoil losses via runoff water throughout the year.

Root-harvested crops are also very susceptible to soil borne pests (and the consequential market-determining skin appearance). With a lower tolerance or threshold for pests such as nematodes, weevils and wireworm compared to other categories, these crops also have a slightly different risk profile regarding pesticide requirements which necessitates further investigation based on crop husbandry and seasonal risk to RWQ.

2.3.2 Grouping

Various cropping systems share similar management practices and production system characteristics that are expected to have related risks to RWQ. This allows the selected crops (underlined) to be grouped into five general categories where recommendations can be extended to other crops with similar risk profiles and characteristics. Note: groupings are subjective and have over-lapping risks.

a) <u>Perennial horticulture / orchards</u> (such as macadamias, avocados, mangoes, citrus, grapes, and other nut and fruit trees). With long-term plantings, tillage requirements tend to be very different to other crops, particularly when mature. New plantings and younger trees often have limited ground cover, combined with long-term land preparation requirements that increase susceptibility to erosion and herbicide residue wash risks. It is therefore beneficial to divide perennial crops into two sub-groups due to significantly different RWQ risk profiles:

   I. New plantings (less than 2 years old and includes land preparation), and

   II. Mature orchards (2 or more years old, following the ALUM (V8) technical definition of perennial being growing for more than 2 years).

   This includes all crops in the ALUM (V8) perennial categories 3.4.0-9 and 4.4.0-9, (excluding bananas (out of scope) and pineapples (separate grouping)).

b) <u>Pineapples</u> have a unique production system and risk profile. Although officially classified as perennial, some cultivars (particularly for the fresh market) are grown within a two-year cycle. They are also a slow growing, high input crop traditionally grown on free draining and highly erodible soils, which increases the risk of nutrient leaching and sediment loss. Their more regular replant interval (2-3 years) positions them closer to seasonal horticulture in terms of almost all risks. *Pineapples form the majority of the shrub berries and fruit category (3.4.5 and 4.4.5).*

The remaining crops as selected (mainly seasonal horticulture) are included in three groups, each having a unique production system. *The recommendations for each of these are likely extended to a variety of fruit, vegetables and herbs from categories 3.5.2, 4.5.2, 3.5.3 and 4.5.3*:

c) Short term seasonal crops (usually with multiple planting windows) including beans, sweetcorn, some herbs and flowers, cabbage, broccoli, lettuce, etc. Because of limited shelf-lives and continuous market requirements, these crops tend to have multiple sequential weekly plantings where land preparation and growing conditions may occur during adverse weather conditions. This category will be referred to as "Continuous supply crops" for reference, although this is not a commonly used term.

d) Mulched crops include melons, tomatoes, capsicums, zucchinis, strawberries, chillies, some flowers, peas and often pumpkins. These tend to be high value, high input crops (pumpkins are a possible exception) usually grown with plastic mulch and drip irrigation, allowing for regular fertigation. Because of the high value, the focus is usually more on maximising saleable yield as opposed to minimising input costs.

e) Root harvested crops such as potatoes, sweetpotatoes, onions, garlic, taro, carrots, radish, turnip, some herbs and irrigated turf (4.5.3-4). These crops need to be dug up at harvest exposing soil to significant erosion and soil degradation risks.

Note: there is some overlap of risks between groupings. For example, most of the mulch and root crops require multiple plantings, similar to continuous supply crops. For this reason there are commodities which may span different groups but which have been categorised based on general production practice and risk of causing RWQ decline.

3 Management practices to improve water quality outcomes

Through the Reef 2050 WQIP, significant work has been undertaken to identify the most critical commodity specific practices impacting on water quality, including critical areas requiring management practice improvements. Like other sectors, the management practices that affect water quality runoff from horticulture activities are outlined in the Paddock to Reef (P2R) Horticultural Water Quality Risk Framework 2017 – 2022 (Appendix I) and ranked in terms of water quality risk outcomes (i.e., Lowest, Low, Moderate and High).

To understand and find solutions to RWQ risks arising from horticulture, the Reef 2050 WQIP 2017–2022 has developed two separate risk frameworks. This includes one for bananas (excluded from scope of this report) and the other for all remaining horticultural crops. The existing 2017-22 framework identifies the major impacts on Reef water quality related to four management strategies (see Table 3).

Table 3: Risk management framework

Management strategies			
Soil management	Pesticide management	Nutrient management	Water management
• Controlling runoff using buffers • Fallow management • In-field erosion control • Inter-row management • Roadway and headland maintenance • Sediment traps	• Calculating pest and crop chemical requirements • Reducing chemical loss to runoff and drift • Integrated Pest Management (IPM)	• Soil testing • Leaf testing • Nutrient budgeting and recording • Fertiliser application methods and • Calculating fertiliser rates	• Irrigation scheduling • Matching irrigation interval and volume to crop requirements and soil limitations • Water reuse

Source: Australian and Queensland Governments (2020a)

The existing framework gives examples from highest to lowest risk as superseded practices, minimum standards, best practice, and innovative / cutting edge practices. This report identifies existing research on horticultural management practice changes (in scope) relating to RWQ risks and the economic outcomes of practice change that reduces risk(s).

Although the latest published Report Card for 2020 (Australian and Queensland Governments, 2022) omits horticulture (recorded as: “Not applicable. Land management targets are currently under review”), previous results give low confidence in accuracy of the data. There remain trend discrepancies between producer numbers, total area and best practice system changes (Table 4).

Table 4: Report cards on horticultural land area managed using best practice systems

	Horticultural land area managed using best practice systems			
Year	2016	2018	2019	2020
Soil	61,561 (72%)	12,948 ha (25.5%)	12,959 ha (25.5%)	N/A
Pesticides	38,687 (45%)	21,585 ha (42.5%)	21,587 ha (42.5%)	N/A
Nutrients	20,605 (24%)	9,062 ha (17.9%)	9,130 ha (18%)	N/A
Average	47%	28.6%	28.7%	N/A
Producers	970	970	970	N/A
Total Area	86,000	50,700	50,700	N/A

Source: Australian and Queensland Governments (2022)

Although this data is valuable it may not represent a true and accurate depiction of land area managed under BMP systems but rather a guide to understanding what may be anecdotally evaluated as BMP (rather than quantified empirically). More work is required to understand what BMP is and how it relates to land areas under horticultural production as there are constraints around what and how practices can be reported. While there remain challenges in validating practice change impacts for horticulture, this does not necessarily invalidate the currently available framework. However, the current framework is due for renewal where the WQIP's are updated every four to five years to incorporate the best available independent scientific advice (provided by the Scientific Consensus Statement).

The new framework is anticipated to include a more output-based focus, but this is not expected to substantially affect the knowledge gaps identified. Only once sufficient agronomic research is completed investigating risks of RWQ decline associated with specific crops and the timing of their production practices will an evidence base allow for refinement of management practices and any economic evaluation for improvement in water quality outcomes.

The following section reviews openly available economic publications aligned with the current P2R Horticultural Water Quality Risk Framework 2017 – 2022 within the GBR catchment. Key practices include soil, pesticide, nutrient and water management.

4 Review of economic case studies

The literature search as detailed in Appendix D identified a lack of research on horticultural economics relating to the current water quality risk framework. This is likely due to the specialised nature of horticultural crops which are grown on small areas within the GBR catchment. Minimum practice standards for horticulture (and grains) have also not yet been finalised and are due in December 2024 (Queensland Government, 2021). To date, the research on the economic implications of practice change and water quality improvement has been mainly focused on the two dominant cropping systems of sugar cane (e.g. Law et al., 2016, Rust et al., 2017, Thorburn et al., 2017, Gillies et al., 2017, Connellan et al., 2022, Poggio et al. (2018)) and bananas (e.g. Harvey et al., 2018, Holligan et al., 2017) in the Wet Tropics and Central regions of Queensland.

Overall, there is a reasonable body of literature available on nutrient level studies linked to crop growth (largely outside of the risk framework). This has been well covered in *RP240: Improving knowledge and research for horticulture and cropping activities* by Soil Catchment and Riverine Processes Group (2022) for the crops in their scope (including macadamias, avocados, pineapples and vegetables), and various industry associations (Horticulture Innovation Australia, 2018), (Horticulture Innovation Australia, 2022), (Citrus Australia, no date). Appendix J also contains a list of studies from Soil Catchment and Riverine Processes Group (2022) with reported water quality impacts measured under field or experimental conditions, according to commodity type and Natural Resource Management region in the GBR catchment. However, none of these studies look at economic impacts.

It should be noted that nutrient studies showed complex relationships for many horticultural crops due to interactions with produce quality having a major impact on shelf-life and marketability (Perkins et al., 2020). Ideal nutrient levels are not easily achieved (Newett et al., 2018), and the economic impact and changes in nutrient input costs may not have a major economic bearing compared to the total value of production, although this is very dependent on the crop in question, and to a lesser extent, on prevailing market prices for both the produce and inputs.

Despite a lack of research relevant to the risk framework categories, the main study that did examine practice change in relation to water quality improvement argued that “amount of fertiliser utilised in intensive vegetable production is of great concern in Australia (Nachimuthu, et al. 2012). There is strong evidence that conventional vegetable production systems in Australia have the potential to cause adverse environmental impacts through leaching of accumulated nutrients to groundwater or via runoff into surface water receiving bodies (Nachimuthu et al. (2012), Chan, et al. (2007), Wells et al. (2002)).8

The sediments and nutrients in runoff water are likely to affect river water quality and downstream ecosystems such as the GBR (Mitchell et al. 2005). These concerns have necessitated a focus on improving the vegetable management practices to reduce the environmental impact of farming practices (Nachimuthu et al. 2017, p. 2)”.

The following sections review literature directly related to the current risk framework areas of soil, pesticide, nutrient and water management practices. The literature searches are also limited to selected crops and comments made to the inclusion of economic data.

4. 1 Perennial crops

There is an increasing body of research relating to general growing practices for perennial crops but very few studies focus on management practice changes that may improve RWQ in relation to the risk framework. The focus crops include macadamias, avocados, mangoes, citrus, and grapes.

4.1.1 Soil Management

Reid (2002) and Keen et al. (2010) looked at soil (and nutrient) loss in macadamia lands (in New South Wales, not GBR catchments) without an economic analysis. Current plantings have evolved to include a mounded bed where tree seedlings are planted. This helps direct rainwater and stemflows away from the trunk to the inter-rows (normally grassed), rather than channelling water along the row where bare or sparsely covered soil exists under trees. Additionally, mounds elevate the growing root system and allow for a more preferential freely drained soil environment, critical to health crop growth.

Australian Macadamia Society fact sheets stress the importance of ground cover in reducing soil and nutrient loss. Reproduced trial results have indicated that after a 50mm rainfall event, a change in soil loss increases from 0.03 t/ha, with 89% ground cover, to 22 t/ha, with 6% ground cover (Queensland Government, 2013). There are also reductions in Nitrogen (N) and Phosphorus (P) losses with increased ground cover (and other benefits, such as reduced evaporation, ground temperature regulation, and beneficial biological diversity). No economic outcomes are presented, and this was a generalised trial, rather than a tree specific one. Similar fact sheets championing ground cover are available within the avocado and mango industries (also excluding economics) (DAF Queensland, 2020).

[8] Harper (2014) did find, as part of project VG09041 (which looked at the impact of vegetable production systems on sensitive waterways) that some crops in the Lockyer Valley demonstrated high efficiency of nutrient input use. However, this was for crops that were not widely grown in the GBR catchment (lettuce, cabbage and broccoli), whereas capsicum and sweet corn grown in the GBR catchment still indicated excessive use of N.

As previously mentioned, new plantings pose significant risk to RWQ decline from sediment in terms of erosion potential. However, there has been no research on the costs and returns of reducing this risk. In mitigation, many of the initial practices are designed to try and minimise erosion and flooding by developing a complete orchard drainage plan. This involves short term risk for long term benefit.

4.1.2 Pesticide Management

According to the 2017 Scientific Consensus Statement, the mean-annual loads of prevalent pesticides (ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine) are estimated (modelled) to be around 12,000kg per year across the GBR (Waterhouse et al., 2017). Measured pesticide data suggests that most pesticides are found in all catchment regions, even though some are in very small quantities. It is pertinent to note that the pesticides found in the major horticultural catchments (such as those rivers in the Burnett Mary), do reflect those chemicals used in horticultural production (with some key differences to the major sugar cane growing areas further north).

Doyle (2015) studied the band spraying of weeds in macadamias (Burnett Mary region), finding that a precision weed spraying system could reduce herbicide use by 50% and deliver large savings whilst still controlling weeds, using WeedSeeker sensors. Partial gross margin analysis indicated a favourable cost saving of over $50/ha from introducing this technology. However, contact herbicides (e.g., paraquat) were applied which are less toxic to the environment when compared to residual herbicides (that require total coverage due to their mode of action). Although economically beneficial, improvements to overall RWQ may be limited.

No other economic studies were identified that measured the pesticide management outcomes on RWQ. It is expected that where pesticides are applied to a large volumetric area with multiple interception points (i.e. large tree surface area), the amount of chemical residue on soil is likely limited to residual herbicides used (especially in new plantings).

4.1.3 Nutrient Management

Many perennial flowering crops tend to go through similar growth cycles (sequentially after harvest: shoot flush, root flush, shoot dormancy, flowering, fruit set, fruit development, root flush, harvest (Horticulture Innovation Australia, 2018)) which require varying amounts of nutrients. This sequence varies according to season and crop, but the general recommendation is to split nutrient applications to target particular responses (Department of Agriculture and Fisheries (DAF), 2015).

There have been numerous studies in most tree crops such as macadamias (Smith, 2016), avocados (Perkins et al., 2020), mangoes (Horticulture Innovation Australia, 2018), and citrus (Citrus Australia, no date), looking at varying levels and timings of nutrient applications and what effect those have on crop growth or quality. While these studies consistently find that frequent and varied applications of nutrients, or the avoidance of excessive applications tend to increase production and quality, they do not examine changes in water quality associated with the different states of nutrient management. Instead of repeating those studies here, a review can be found in RP240: Improving knowledge and research for horticulture and cropping activities (Soil Catchment and Riverine Processes Group, 2022).

The most relevant were two similar studies examining nutrient losses (N and P) from a macadamia orchard in the Burnett Mary catchment. Stork et al. (2009) investigated surface losses of N from a coastal macadamia plantation over five runoff events. The estimated annual loss of total N in runoff was 0.26 kg N/ha per year, representing a minimal loading of N in surface runoff when compared to other studies. While this estimate was comparatively low, there was evidence that the stream catchment and associated agricultural land uses were already characterised by significant N loadings that could pose eutrophication risks. In a follow-up study, Stork and Lyons (2012) examined P losses along similar lines but found concentrations of Dissolved Inorganic Phosphorous (DIP) in runoff were 20–200 times higher than those found in other coastal catchments in Queensland. High concentrations of DIP were present in the topsoil of the non-fertilised, inter-row areas of the farm, and this was attributed to transfer and deposition of DIP from adjacent fertilised tree beds during storm related overland flow. However, together with N losses in runoff, reported previously, an N: P molar ratio of 2:1 was contained in the farm runoff. This was well below the growth-limiting threshold for aquatic organisms, as determined by the Redfield ratio of 16:1 (N:P). Neither study, however, analysed alternative practices and no economic comparisons were undertaken.

Many orchards use composted materials to both mulch the soil and provide nutrients, but no work has been found to quantify the resulting downstream effects of these practices.

4.1.4 Water Management

Water and irrigation management are important aspects of perennial crop management (Zapp, 2022). Drip or micro-sprinkler irrigation is used extensively, increasingly in new orchards, in combination with moisture sensing devices and automation. The major key weakness is compacted inter-rows reducing infiltration rates that can contribute to significant runoff. This is compounded by stem flow, particularly in macadamias. However, no research has been identified that analyses changes in water management, or what impact this has on RWQ.

4.2 Pineapples

4.2.1 Soil Management

Pineapples are very susceptible to phytophthora root rot, and great care is taken to plant them in soils that drain well. Pineapple production currently requires extensive tillage operations to prepare the soil for new plantings despite often being grown on soil with low CEC (Cation Exchange Capacity) and organic carbon, with a weak structure, and a reasonable slope (more than 2%). Slopes between 2 – 6 % are considered best for pineapple growing (DAF Queensland, 2013a), but historically have reached 30% or more. Weak soil with little ground cover on steep slopes reflect a high risk of sediment loss. Identification of this risk prompted various studies, including Ciesiolka et al. (1995), Palis et al. (1997), Coughlan and Rose (1997) and Yu et al. (2000). Recommendations included having a maximum row length according to slope, planting pineapples in the inter-row at regular intervals, applying soil stabilising chemicals, using contour banks and drains, in addition to having strategically sized and placed sediment traps based on area.

Ciesiolka et al. (1995) found that on steep sloping land, soil erosion in 7 m and 12 m long rows was very similar but increased by four times for 22 m rows. However, they did not determine the economic impact in adjusting row lengths.

Palis et al. (1997) studied the effect of slope length on runoff and soil loss, and the loss and enrichment ratio of nitrogen from steep slopes planted to pineapple on three (steep) sites. They found that total soil loss per unit area in each erosion event increased with increasing slope length, but similarly did not examine the cost of changing the slope length. Some producers have installed contour banks at regular intervals[9] but without analysing the costs or returns.

Yu et al (2000) used a Water Erosion Prediction Project method to measure soil loss predictions under three (3) scenarios (bare, farmers' conventional practice, and mulching of the furrows). The model was only accurate in predicting one of the treatments, and under certain conditions. No economic analysis accompanied these treatments or has been applied since, but past literature suggests that soil loss risks in pineapples have been a well-researched issue for some time given its prevalence in this crop.

There have been a number of factsheets on living mulches (such as oats, sorghum or millet) in pineapple inter-rows produced for SEQ catchments which would be applicable for GBR catchment growers (Department of Primary Industries and Fisheries, 2008). A basic partial budget indicated that there could be a cost-neutral change to replacing some herbicide sprays with a planting (and subsequent termination) of a living mulch that reportedly had no noticeable difference in pineapple yield, but contributed to reductions in topsoil loss.

More recently, nine different treatments were trialled to reduce in furrow erosion on a newly planted pineapple block (Abel, 2021) in Valdora, SEQ (notably, this is marginally outside of the GBR catchment though soil types and practices are comparable to GBR growing locations). This was subsequently reduced to five treatments, and there was a simple costing done on the installation of each treatment, as well as an estimation of topsoil saved. There was a very effective treatment using hydromulch (cane mulch sprayed with a polymer glue) which completely halted erosion for the season in question, but this came at a high cost of installation ($6,650/ha), with no data on differences in potential yield or future cost changes. The next most effective option was whole pineapple plants from the previous crop being laid in the furrow to filter out sediment. This reduced sediment loss from over 50 Mt/ha to under 10 Mt/ha at a tenth of the cost of the hydromulch. However, there was no long-term analysis on what this topsoil saving meant for the farm, so all the treatments resulted in a net cost to the producer (although a potential savings figure was theorised).

Griffin (2021) explored a range of interventions in the Wide Bay area, although there has not been an economic analysis done on the results. The trial was more a demonstration of different options for a field-day rather than a scientific trial. Literature from the past 20 years shows that the challenge of sediment loss is widely acknowledged, however, there is no definitive, cost-effective solution that has been widely adopted by growers.

4.2.2 Pesticide Management

Pineapples are propagated from tops/crowns, slips, or suckers and consequently there is an extended period of slow growth as the plant establishes new roots and shoots. Because of this growth pattern pineapples are susceptible to weed competition during crop establishment. Weeds are managed via the use of residual herbicides such as Diuron and Bromacil (leaving the soil bare). These chemicals

[9] https://www.growcom.com.au/2021/10/26/cutting-the-crop-with-pinata-farms/ (Growcom, 2021)

have been known to persist and move into waterways. Griffin (2021) investigated the effectiveness of partial sediment traps to capture N, P and chemical residues in runoff water, which was then exposed to UV radiation for several months to reduce levels. While this showed some decline, there was no economic analysis, nor was it a practical solution for the whole season, but rather a partial small-scale demonstration trial.

4.2.3 Nutrient Management

Pineapples pose an elevated risk in other areas: the amount of N applied per ha is recommended in the pineapple growers manual to be 870 – 940kg within a three-year period (of plant and one ratoon crop) (Carr, 2022). Due to the soil types favoured in pineapple production, evidence of appreciable N leachate losses have prompted investigation for many years. Coughlan and Rose (1997) found large potential losses for N and other nutrients from both runoff and leaching.

Irvine-Brown et al. (2022) examined N budgeting for water quality improvement in pineapple production systems of SEQ. While the site was outside of the reef catchment, the focus was deep drainage (leachate) to shallow ground water. The main soil types present in the Pumicestone catchment have inherent low fertility and are susceptible to nutrient losses via leaching, similar to most soils planted to pineapples in reef catchment areas. The study identified N loading in waterways was impacted by rainfall volume and frequency. Agronomic timing of N applications to meet plant demand was imbalanced (especially when excess N was applied to newly planted crops). Deep drainage was the predominant N loss pathway in major soil types of the catchment. The study did not include an economic analysis.

4.2.4 Water Management

Pineapples are very susceptible to phytophthora root rot, which has traditionally been dealt with by maintaining a low soil pH (<4.5 pH) and ensuring good drainage (DAF Queensland, 2013b). In order to avoid water logging there must be lateral drainage, often combined with high beds (0.2-0.6m) to protect roots. The result is increased runoff potential with higher RWQ decline risks (particularly from sediment) associated with steeper slopes, absence of ground cover and options for contour planting.

4.3 Continuous Supply Crops

The focus crops include seasonal vegetables crops, beans, and sweetcorn. These crops are often grown in rotation with minimal disturbance to the soil at harvest.

4.3.1 Soil Management

While the literature search did not provide any relevant results for review, the risk is likely similar for almost every crop that is planted into freshly cultivated soil. The reason horticultural crops may pose some risk is because these crops are often planted according to planned maturity to harvest windows, irrespective of weather conditions. The risk is exacerbated by price spikes following shortfalls of produce in the market. This provides financial incentive to plant consistently, especially when bad weather events affect planting and therefore supply and subsequently prices at market.

4.3.2 Pesticide Management

Continuous supply crops are normally rotated with others to maintain soil health. This limits the use of residual herbicides due to restrictive plant-back periods[10] for the subsequent crop. Although there was no literature available on this topic, it is expected the risk of harmful pesticides to RWQ outcomes would be lower for these crops with the dominant use of contact pesticides.

4.3.3 Nutrient Management

Harper (2014) investigated the environmental effects of vegetable production on sensitive waterways at various sites, referencing two centres in the GBR catchment. In particular, N application rates on sweetcorn grown in the Bowen-Gumlu area were analysed. While concluding that many recommendations may be excessive, there was no accompanying research on yield and quality changes under different regimes, nor any economic analysis, though, irrigation management was indicated as a key driver of N loss beyond the root zone. This study also included nutrient application results that varied according to location, which could be construed as soil type (not crop) being probably the main determinant of nutrient loss in the sandier soils in Bowen compared to Lockyer Valley vertisols. Given the need to maintain consistent supply of these crops to meet demand in the market there is arguably a potential reliance on a luxurious supply of nutrients such as N and P regardless of the crop stage nutrient demand to meet growth requirements, particularly on weaker soils. Such nutrient management practices may pose considerable risk of RWQ decline when coinciding with adverse weather events which exacerbate leaching or run-off, though crop stage could be an important factor.

4.3.4 Water Management

Continuity of supply is best achieved by ensuring crops have adequate moisture. It is assumed that irrigation is carefully managed, but no literature was found dealing with risk to RWQ in this regard.

4.4 Mulched Crops

An important consideration is the use of plastic in mulch cropping systems. However, the emerging threat to the Reef defined under the Reef 2050 WQIP identifies micro-plastics as the prime concern. Although plastic mulch could be considered a concern for due to it being a non-biodegradable waste product, it is excluded from the economic literature review, given it is not a micro-plastic. The focus crops include melons, tomatoes, capsicums, and pumpkins.

4.4.1 Soil Management

Detailed studies examining practice change impacts on both risk to RWQ and crop yields was done by Nachimuthu et al. (2013, 2017) in the Burnett Mary catchment. They examined capsicum and zucchini crops grown in summer 2010/11 and winter 2011 respectively, using four different management practices:

[10] A plant-back period or interval is the minimum period of time between a pesticide treatment and the planting of the next crop.

- Conventional - plastic mulch, bare inter-row conventional tillage and commercial fertiliser inputs.
- Improved - improved practice with plastic mulch, inter-row vegetative mulch, zonal tillage, and reduced fertiliser rates.
- Trash mulch - improved practice with cane-trash or forage-sorghum mulch with reduced fertiliser rates, minimum or zero tillage.
- Vegetable only - improved practice with Rhodes grass or forage-sorghum mulch, minimum or zero tillage, reduced fertiliser rates).

Results showed that improved practice and trash mulch systems reduced sediment and nutrient loads by at least 50% more than conventional systems. However, the improvement in runoff water quality was accompanied by yield reductions of up to 55% in capsicum and 57% in zucchini under trash mulch systems, suggesting a commercially unacceptable trade-off between water quality and productivity for a practice change. The current study has shown that variations around improved practice (modified nutrient application strategies under plastic mulch, but with an inter-space mulch to minimise runoff and sediment loss) may be the most practical solution to improve water quality and maintain productivity. However, more work is required to optimise this approach and thus reduce the size of any potential productivity and profitability gap that would necessitate an expensive policy intervention to implement.

4.4.2 Pesticide Management

No literature was found relevant to mulched crops that contained economic studies relating to pesticide management. However, the use of mulch can be considered to significantly reduce the requirements of herbicides (Horticultural Research and Development Corporation, 1996).

4.4.3 Nutrient Management

Due to the high value of production, crops grown under mulch tend to include high nutrient application rates to maximise production per hectare. As mentioned, Nachimuthu et al. (2017) showed that over the two crop rotations, the improved practice and trash mulch systems reduced nutrient losses by at least 50% compared to conventional systems. The residual soil nitrates that accumulated at the end-of-break crop cycle, however, were lost by deep drainage before the subsequent sugarcane crop could utilise it. Also, the improvement in runoff water quality was accompanied by a yield reduction suggesting an unacceptable trade-off between water quality and productivity as a practice change consideration.

Olsen (1992) examined capsicum grown in the Burnett Mary at five different N application rates (from 0 to 280kg N/ha). The highest marketable yields corresponded with recommendations between 210kg and 280kg N/ha. It was estimated that 46-91kg/ha of the applied N had the potential to be lost from the system via leaching, denitrification and/or runoff where overall crop uptake was calculated at 140kg N/ha. However, with the financial impact of lower yields, there remained little incentive to reduce rates. Despite large changes in costs and revenue, no economic analysis was included, nor measurement of actual losses to the environment.

4.4.4 Water Management

With drip irrigation dominating these cropping systems, irrigation occurs frequently at low flow rates helping to meet crop water requirements. Creating the correct soil moisture conditions prior to land preparation can be a challenge for drip irrigation systems being more suited to directed irrigation. It is also prone to tillage operation damage sitting on or just below the surface. No suitable literature was identified as relevant to the relationship between water management practices and RWQ impacts.

4.5 Root Crops

The crops identified by area impact include potatoes and sweetpotatoes. These require significant disturbance of the soil at harvest. Additionally, these crops require high N and P nutrition at key times to facilitate profitable production as well as reliance on agri-chemistry to suppress pest and diseases.

4.5.1 Soil Management

Some horticultural crops are thought to require a fine tilth to maximise seed to soil contact which can affect germination or sprouting speed, and uniformity. Common practice for sweetpotato growers is to rotary hoe the upcoming planting blocks several times before planting.

While it is obvious that crops whose saleable production originates in the soil results in soil disturbance at harvest, there has been surprisingly little research done on how to limit subsequent erosion and loss of topsoil. The only studies available related to N rate impacts. There is a study underway at the Bundaberg Research Facility investigating semi-permanent beds however, there is a complex relationship with production and quality, disease, and tilth (Langenbaker, 2021).

The other area of concern is in the early crop stages, repeated cultivation is one of the management practices regularly used to control weeds. This is positive for reducing residual chemical risks but exposes the land to potential sediment loss if followed by heavy rain. This trade-off has not been studied.

4.5.2 Pesticide Management

Some nematicides and insecticides, such as Fipronil are important soil pest control methods that have a negative effect on aquatic life (Tingle et al., 2003), but are effective in reducing product skin defects, important for marketability. At this stage, there is no literature found relating to root crop pesticide management with regards to RWQ. However, the Bundaberg Research Facility trial as mentioned already is also investigating integrated pest and disease management options to reduce soil borne issues via application of different amendments and compost.

4.5.3 Nutrient Management

As with many horticultural crops, root crops grow best in well-drained soils, which are pre-disposed to nutrient losses via leaching. While there has been work done on ideal N levels in potato crops, none have examined economic or RWQ outcomes at different rates of N.

4.5.4 Water Management

Irrigation is not only used to grow crops, but in the case of sweetpotatoes, it is used to help new tips to sprout. On hot soil in summer, this means irrigation is also used to cool the soil, in excess of plant growing requirements, which can lead to leaching of the basal fertiliser as the plant is not able to take up sufficient nutrients when newly planted. This can theoretically be partially resolved via controlled-release fertilisers (CRF's), though no literature can be found on changes in N losses or economic implications of using more costly fertiliser products such as CRF's within such root crops.

4.6 General Horticulture

Stork et al. (2007) investigated a range of crops in the Burnett Mary catchment including macadamias, sweetcorn, and capsicum (as well as sugarcane), finding applications of N and P well in excess of crop requirements, as well as the presence of the herbicides diuron and ametryn. However, no economic analysis accompanied these findings. One alternative management practice option was suggested for the vegetable crops related to better nitrogen use efficiency (NUE) derived from the higher densities associated with dual (vs. single) row cropping, but without any economic analysis.

Thorburn & Wilkinson (2013) also noted that substantial N fertiliser is applied to high value horticultural crops in GBR catchments, but simplistically suggested that the primary path to reducing N losses from cropped lands will be through reducing N applications.

However, this is more an assumption of the problem than specific solutions that were analysed and costed. It also assumes that farmers apply excess N, regardless of the cost. Instead, Heisswolf et al. (2010, p. 10) reasoned "*that it is more a question of growers not knowing exactly what the optimal application rates are. Research and technology to improve productivity and profitability can also address environmental issues associated with off-site movement of nutrients. Growers often use drip irrigation and frequent fertigation as this system conserves water and allows for accurate and timely placement of fertiliser. However, fertiliser recommendations are based on empirical data rather than calibrated soil and plant tissue diagnostic indices, and they identified large gaps in available input data (critical soil P test levels, crop growth cycles, nutrient uptake and removal data) for a number of vegetable crops. There is a need to develop science-based tools for objectively assessing and facilitating improved best practice nutrient management on a soil-, site- and crop- specific basis."* A major challenge for horticultural growers is the number of variables considered for optimal nutrient rates, especially in fruiting crops, and particularly when the quality of fresh market produce is important (e.g., size, colour, etc.).

Interestingly, Rolfe & Windle (2011) used auction mechanisms to reveal costs for water quality improvements in GBR catchments and found that horticulture and dairy provided the most cost-effective tender systems. An example of providing on-the-ground economic incentives without the enforcement of regulation.

4.7 Overview / Summary

Review of the available literature identifies significant gaps in the understanding of the impact horticultural management practices are likely to have on RWQ. Table 5 presents a summary of the overall review relating to each management practice, group and expected risk levels based on the differences between production systems.

Table 5: Subjective RWQ risk ratings per grouping

Grouping	Management risk category				Studies
	Soil	Pesticide	Nutrient	Water	
Perennial Crops	New - High Old - Low	New-Medium Old - Low	Medium	Low	Stork et al. (2007, 2009, 2012), Doyle (2015)
Pineapples	High	High	High	Low	Ciesiolka et al. (1995), Coughlan & Rose (1997), Palis (1997), Yu (2000), Abel (2020); Griffin (2021)
Continuous supply crops	Medium	High	Medium	Medium	Stork et al. 2007, Harper et al. 2014
Mulch crops	Medium	Medium	High	Medium	Nachimuthu et al. 2017
Root crops	High	High	Medium	Medium	-

Note:
The risk ratings are subjective (although partially confirmed by Soil Catchment and Riverine Processes Group, (2022)) and will differ between management systems. Based on information and the crop systems reviewed, the above risk ratings are used to prioritise future research priorities.

5. Key findings and knowledge gaps

The intent of the Reef Action Plan 2.4 is to "Identify and address barriers to change and practice improvement uptake through programs and policy." The method by which this is achieved is to conduct economic evaluations to validate the economics of management practices that improve water quality" (Australian and Queensland Governments, 2018b, p. 31).

The key findings from both the crop identification process and literature review are included as follows:

- Horticultural crops are numerous, and often limited in terms of area grown. Approximately two-thirds of horticultural area is planted to perennial crops.
- The most prevalent crops (according to area grown) include five perennial crops (macadamias, mangoes, avocados, citrus, pineapples and grapes) and seven seasonal crops (beans, sweetcorn, melons, potatoes, capsicum, tomatoes and pumpkins).
- Production systems as a broad generalisation tend to be managed more intensively and with higher inputs per hectare compared to other crops. This has been found to lead to a higher risk of nutrients (particularly N and P) reaching the Reef.

- For multiple short-term crops grown on the same area within a year (which is often the case with seasonal vegetable crops), actual annual fertiliser rates will be the sum of all applied.
- The value of horticultural production per hectare varies considerably, and this can influence how crops are grown and risks approached (e.g., less consideration of input cost impacts when crops are higher in value).
- Broad generalisations can be misleading with such a diverse range of crops - there are many different crops, varieties and accompanying management systems, so horticulture should not be viewed as one homogenous group.
- Confidence in the accuracy of ‘up-to-date’ areas grown remains low but is improving for the main fruit and nut tree crops.
- As per Appendix G, 95% of the fruit and nut tree growing areas are centred on only nine river basins. These are also in the main catchments as seasonal vegetables. This may change in future as tree crops, and particularly macadamia expand as a result of land use change to high value horticulture.
- There has been very little work found to date about measuring in-scope horticultural risk impacts on the GBR.
- There are no economic studies found that both “identify and address barriers to change and practice improvement.”

Overall, there are significant knowledge gaps validating the economics of practice change relevant to RWQ impacts. However, this information is critical in the promotion and adoption of environmentally responsible practices that also have economic benefit for growers.

5.1 Knowledge gaps

5.1.1 Establishing optimum nutrient levels

There is a significant gap in understanding the production-based interactions between nutrients and crop husbandry and the quality of horticultural products. Research into these agronomic interactions needs to be undertaken to inform the economic parameters and determine the optimum strategy for growers. Existing programs such as the Banana Nutrient Trials (RP191) highlights the importance of including different disciplines (growers, agronomists and economists) to address a specific research question.

In perennial crops that derive production from a flowering event, there is an element of self-regulation where excess N levels or infrequent high application rates can lead to poor production outcomes as excessive nutrient levels can lead to flower abscission (reducing yields), higher incidence of pests and disease, and poor-quality shelf life. Although this self-regulation should be positive for RWQ outcomes, the many variables considered each season make it difficult to define any ultimate best management practice. Although guidelines are available (see Appendix L for N considerations in avocado production), Newett et al. (2018) found N applications in avocado plantations ranging from 69-528 kg/ha with the average at 212 kg N/ha/year. This despite a recommended average of 110 kg

N/ha/year (for mature trees) according to the industry's own Best Practice Resource (DAF Queensland, 2013b).

5.1.2 Retaining topsoil on farm

Improved guidelines on soil management are key for horticultural crops, especially those grown on weakly structured soils, that have regular plantings despite weather risks, that are dug out of the ground for harvest and those that require extensive land work prior to planting (e.g., new macadamia plantings, crops requiring extensive pre plant tillage operations). While soil retention is important for long-term sustainability, there is often a trade-off with management practices that are economical or practically viable. Therefore, appropriate management of risk of soil loss in the form of sediment collection areas as a key component of any best management practice may be necessary despite the complexity of economically incentivising this.

Current practices, designed to reduce erosion, can vary widely between crops and production systems. The current framework suggests improved sediment, nutrient and pesticide management practices for a range of different sectors despite significant variation. Best management practices tailored to suite specific crops or production systems remain a challenge for the horticultural sector.

5.1.3 Pesticide translocation

Although there are stringent food safety requirements that require growers of certain crops to manage food safety risks thereby limiting application (Freshcare, 2022), there has been very little research done on pesticide use in horticulture on downstream catchment residue levels. Due to the frequency of use, and the range of different molecules used, horticultural crops are a likely risk and require further investigation, especially relative to economics of improved spray efficiency or alternative methods to achieving control of pests and diseases .

5.1.4 Irrigation and rainfall interactions.

Many horticultural crops have advanced irrigation infrastructure which enables adequate levels of water to be applied. This interacts with soil, pesticide and nutrient risks, particularly when excess rainfall events occur. However, there is no clear understanding of the exact economic relationships between these linked risks. Given water is often the key limiting input there is considerable scope to enhance economic incentive for practice change where water related interactions show benefits.

6. Future research priorities

There is a significant need for both economic and agronomic research on horticultural practices that affect RWQ outcomes. Prioritising key areas for future whole of farm practice change economic analysis may be approached by identifying the crops and production systems with the:

- largest current cumulative potential impact on RWQ (i.e., crops with the largest areas grown within GBR catchments)
- largest future projected cumulative potential impact on RWQ (i.e., crops that are expected to continue expanding within GBR catchments)
- where agronomic research is available on such crops and
- where agronomic research is available from other geographic locations on such crops, or on crops with similar production risk profiles.

Within the scope of the report, crops that were the dominant by area within GBR catchments were identified as the highest likely contributors to RWQ outcomes. Future research on individual crop impacts is required where smaller areas of highly impactful crops could have significantly higher impact on RWQ. While intensive horticulture has been excluded from scope, it is an area of increasing importance with potentially much higher impacts per hectare compared to traditional horticulture, and as such would warrant further investigation. However, for this report, based on the research available and understanding of the various cropping systems in scope, the areas of priority are determined as follows:

High priority

The following are identified as high priority areas for future research:

- Newly planted macadamia areas that are considered a high sediment risk due to currently significant expansion programs within the GBR catchment. This requires a focus on management practices that minimise topsoil loss and general erosion, and other issues that may arise due to the long-term nature of tree cropping. The flow-on effects of potential downstream flooding also need to be considered in the system design, including infiltration improvement strategies that mitigate this risk.
- Economically optimum nutrient levels in avocados due to the current discrepancies in N application rates. This is despite strong linkages to yield and fruit quality implications.
- Sediment and resultant nutrient and agri-chemical losses through the establishment of pineapple crops on traditionally weak soils. Past research indicates both the severity and the difficulty in finding viable solutions, yet new focus on combined agronomy and treatment system approaches may yield new opportunities.
- Controlled traffic and reduced tillage work well in low margin crops, but these are still relatively under-explored practices in many horticultural crops. In crops such as sweetpotato, haul-out tractors intermittently drive on top of the seedbed creating long term compaction issues. Furthermore, there is a paucity of info on sweetpotato – an industry in close proximity to the coast with important pesticide requirements, making it a high priority for further research.

Producers are more likely to understand the risks involved in changing (or more importantly, <u>not</u> changing) to an improved system if *both the environmental and economic consequences are clear*. There is a need to determine the whole-of-business impact of the adoption of the management practices in the P2R water quality risk framework, including detailed consideration of the implementation phase on business outcomes. Given that a new framework is due out this year, this is very timely.

Medium priority

The following are identified as medium priority areas for future research:

- Plastic use in mulched crops has a negative effect on the environment. Biodegradable or natural alternatives may be a solution; however, past research shows current alternative options as economically unviable.
- Demand for the 'continuous supply' of fresh produce (such as beans and sweetcorn) increase runoff risks significantly. Developments in storage and shelf-life could mean that a smaller

percentage of land is put at risk during extreme weather events, as would better forecasting tools and interpretation of agronomic information to assist decision making at paddock scale.

Low priority and data requirements

The following are identified as areas for future research:

- Available horticultural area information is dated, and by the very nature of opportunity cropping, highly variable. The use of modern satellite imaging (i.e., remote sensing technology) to identify different crops should be expanded.
- Improving identification of land managed under best management practice, and better defining BMP for diverse production systems.

Other considerations

Major buyers of horticultural produce have initiated sustainability improvement programs that highlight the potential of market driven practice change at farm level. For example, Woolworths note in their Group Sustainability Plan 2025 (Woolworths Group, 2020) that “by 2022, in collaboration with our farmers, suppliers and other partners, we will carry out and publish a review of the potential for adopting sustainable and regenerative agriculture practices across our fresh food supply chain aimed at improving areas such as soil health and water efficiency in high-risk areas and will provide an annual update on our actions to implement.” The programs however remain unclear on how producers are likely to benefit through a change in practice and what economic incentives are.

It would be beneficial to gain a better understanding of the potential economic improvements from using existing Ag-Tech. This could include assessment of freely available or low-cost information that could enhance decision making at the paddock scale to improve management of risk and causes of RWQ decline.

Growcom has initiated a Reef Certification which helps producers audit on-farm processes that identify and attempt to minimise water runoff quality issues (Growcom, 2018). Importantly, processes should also meet general requirements for long term financial sustainability. In these cases, market rewards for certified growers are expected to increase adoption. More work is required on substantiating credentials to underpin market reward-based mechanisms which can differentiate products in the marketplace. This could include further investigation into auction mechanisms to reveal costs for water quality improvements, and stackable credit benefits (e.g., reef and carbon credits).

In conclusion, economically beneficial practices are more likely to be adopted by producers. From targeting niche markets to reducing costs, improved management practices require both environmental and financial outcomes that are significant enough for wider industry promotion.

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Appendix A: Australian Land Use and Management Classification Version 8 (October 2016) – Agricultural Land Use (Non-Horticultural)

3	Production from Dryland Agriculture and Plantations	4	Production from Irrigated Agriculture and Plantations
3.1.0	**Plantation forests**	**4.1.0**	**Irrigated plantation forests**
3.1.1	Hardwood plantation forestry	4.1.1	Irrigated hardwood plantation forestry
3.1.2	Softwood plantation forestry	4.1.2	Irrigated softwood plantation forestry
3.1.3	Other forest plantation	4.1.3	Irrigated other forest plantation
3.1.4	Environmental forest plantation	4.1.4	Irrigated environmental forest plantation
3.2.0	**Grazing modified pastures**	**4.2.0**	**Grazing irrigated modified pastures**
3.2.1	Native/exotic pasture mosaic		
3.2.2	Woody fodder plants	4.2.1	Irrigated woody fodder plants
3.2.3	Pasture legumes	4.2.2	Irrigated pasture legumes
3.2.4	Pasture legume/grass mixtures	4.2.3	Irrigated legume/grass mixtures
3.2.5	Sown grasses	4.2.4	Irrigated sown grasses
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
3.3.5	Sugar	4.3.5	Irrigated sugar
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 3.5.0	*Perennial Horticulture and Seasonal Horticulture**	*4.4.0 4.5.0*	*Irrigated perennial horticulture and Irrigated seasonal horticulture**
3.6.0	**Land in transition**	**4.6.0**	**Irrigated land in transition**
3.6.1	Degraded land	4.6.1	Degraded irrigated land
3.6.2	Abandoned land	4.6.2	Abandoned irrigated land
3.6.3	Land under rehabilitation	4.6.3	Irrigated land under rehabilitation
3.6.4	No defined use	4.6.4	No defined use - irrigation
3.6.5	Abandoned perennial horticulture	4.6.5	Abandoned irrigated perennial horticulture

*Expanded in Table 1 in the main report. Included here as a reference only.

Appendix B: Crops contained in ALUM V8 for Horticulture

Nuts	Fruit (cont.)	Vegetables and herbs		Flowers and bulbs
Almonds	Jackfruit	Arrowroot	Marrows and squashes	Australian native flowers
Brazil nuts	Kiwifruit	Artichokes	Mint	Bulbs
Cashews	Kumquat	Asparagus	Mushrooms	Calendula
Chestnuts	Lemons	Beans	Okra	Carnations
Hazelnuts	Limes	Beetroot	Onions	Chrysanthemums
Macadamias	Loganberries	Bitter melon	Oregano	Daffodils
Pecan nuts	Longans	Broccoli	Parsley	Flowers and foliage
Pistachios	Loquats	Brussels sprouts	Parsnips	Gerberas
Walnuts	Lychees	Burdock	Peas	Lavender
	Mandarins	Cabbages	Peppermint	Lilies
Fruit	Mangoes	Capsicums	Potatoes	Orchids
Apples	Mangosteen	Carrots	Pumpkins	Proteas
Apricots	Melons	Cauliflowers	Radishes	Roses
Avocados	Mulberries	Celery	Rhubarb	Tropical flowers
Babacos	Nashi pears	Chamomile	Rocket	Tulips
Bananas	Nectarines	Chervil	Rosemary	
Blackberries	Olives	Chicory	Sage	
Blackcurrants	Oranges	Chillies	Silverbeet and spinach	
Blueberries	Passionfruit	Chinese cabbages	Snowpeas	
Boysenberries	Pawpaws	Chives	Spring onions and shallots	
Carambolas	Peacharines	Coriander	Sprouts	
Cherries	Peaches	Cucumbers	Sugar beet	
Chokos	Pears	Echinacea	Swedes	
Coconut	Pepinos	Eggplants	Sweet corn	
Cranberries	Persimmons	Fennel	Sweetpotatoes	
Custard apples	Pineapples	French beans	Tarragon	
Dates	Plums	Garlic	Thyme	
Dragon fruit	Pomegranate	Gherkins	Tomatoes	
Feijoa	Quinces	Herbs	Truffles	
Figs	Rambutans	Kumara	Turnips	
Gooseberries	Raspberries	Leeks	Vegetable seeds	
Grapefruit	Redcurrants	Lemongrass	Vegetables	
Grapes	Rosella	Lettuces	Zucchini	
Grapes - dried	Strawberries	Marjoram		
Grapes - table	Tamarillo			
Grapes - wine	Tangelos			
Guavas	Watermelons			

Source: ABARES (2016)

Appendix C: Reef catchment areas

Catchment	Reef Plan* (ha)	ABARES# (ACLUMP) (ha)	QLUMP** (ha)	Proposed (ha)
Burnett Mary	5,302,199	5,571,310	5,583,785	5,571,310
Fitzroy	15,565,385	15,670,231	15,717,991	15,670,231
Mackay Whitsunday	900,750	926,803	936,645	926,803
Burdekin	14,068,614	14,085,990	14,089,680	14,085,990
Wet Tropics	2,172,528	2,220,804	2,222,764	2,220,804
Cape York^	4,298,080	10,679,174	13,699,510	4,298,080
Total	42,307,556	higher	highest	42,773,217

* Source: Department of Environment and Science, Queensland (2021). This is from interactive mapping reports.

Source: ABARES (2021). This is the summation of ALUM V(8) categories 1-6

** Source: Queensland Government (2020). This is from multiple data sets (one per catchment).

^ Source: Australian and Queensland Governments (2020b).

Appendix D: Searching the literature – method

The document review was intended to look for a specific combination of factors:

1. Articles dealing with horticultural crops (rather than sugarcane or grazing for example)
2. Articles based on the study area in question (GBR catchment) rather than other areas with different factors and possibly unapplicable solutions.
3. Articles looking at the effect on runoff water quality, such as levels of (Dissolved Inorganic) Nitrogen, rather than Nitrogen applied to crop for crop growth; and,
4. Articles that looked at the economic implications of a practice change that influenced RWQ.

The literature search was compiled using the following parameters:

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] (horticulture OR orchard OR avocado OR macadamia OR mango OR citrus OR pineapple OR grape OR vegetable OR beans OR sweetcorn OR "sweet corn" OR melon OR potato OR tomato OR pumpkin OR capsicum)

[region] ("Great Barrier Reef " OR “GBR” OR “reef catchment” OR Queensland OR "Cape York" OR Fitzroy OR Burdekin OR "Burnett Mary" OR "Mackay Whitsunday" OR "Wet Tropics" OR "Dry Tropics" OR "Terrain NRM")

[GBR science category] (nitrogen OR phosphorous OR nutrient OR pesticide OR herbicide OR insecticide OR fungicide OR sediment OR environment OR "Run off" OR "runoff" OR "run-off" OR "Water quality" OR hort360 OR "Hort 360" OR "Best Management Practice")

[economic analysis] (economic OR "Gross margin" OR profit OR revenue OR cost OR monetary OR financial OR "net present value")

(TITLE-ABS-KEY AND TITLE-ABS-KEY AND TITLE-ABS-KEY AND TITLE-ABS-KEY)

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

(TITLE-ABS-KEY(horticulture OR orchard OR avocado OR macadamia OR mango OR citrus OR pineapple OR grape OR vegetable OR beans OR sweetcorn OR "sweet corn" OR melon OR potato OR tomato OR pumpkin OR capsicum)

AND TITLE-ABS-KEY("Great Barrier Reef " OR "GBR" OR "reef catchment" OR Queensland OR "Cape York" OR Fitzroy OR Burdekin OR "Burnett Mary" OR "Mackay Whitsunday" OR "Wet Tropics" OR "Dry Tropics" OR "Terrain NRM")

AND TITLE-ABS-KEY(nitrogen OR phosphorous OR nutrient OR pesticide OR herbicide OR insecticide OR fungicide OR sediment OR environment OR "Run off" OR "runoff" OR "run-off" OR "Water quality" OR Hort360 OR "Hort 360" OR "Best Management Practice") AND AFFILCOUNTRY(Australia))

AND TITLE-ABS-KEY(economic OR "gross margin" OR profit OR revenue OR cost OR monetary OR financial OR "net present value").

Due to the small number of results generated, a search was also completed with this last section relating to economic analysis being dropped from the grouping, which increased the number of hits from 26 to 190, although the majority were irrelevant.

b) A Google Scholar search was also applied with the same keywords as above, presented through QG agency, industry-specific, regional-body and other non-government websites.

Results obtained from a) and b) were captured in an Excel spreadsheet.

In addition, the following industry associations or bodies were contacted for advice:

Growcom

AUSVEG (Industry Representative Body for Vegetable and Potato Growers)

Hort Innovation

Bundaberg Fruit and Vegetable Growers

Bowen Gumlu Growers Association

Australian Macadamia Society

Avocados Australia

Australian Mango Industry Association

Citrus Australia

Australian Pineapples

Australian Table Grape Association Inc.

Melons Australia

Australian Sweetpotato Growers Inc

Appendix E. ABS area data for agricultural commodities by GBR NRM* region (2020-21)

ABS 2020-21 Data	Burnett Mary	Fitzroy Basin	Reef Catchments	North Qld Dry Tropics	Terrain NRM	Cape York	Grand Total
Land use - Land mainly used for agricultural production - Total area (ha)	3,120,424	13,183,083	543,756	11,103,503	769,084	1,570,668	30,290,516
Land use - Land mainly used for cropping and improved pastures - Total area (ha)	1,153,870	6,597,911	263,262	2,786,730	280,620	31,852	11,114,245
Land use - Land mainly used for crops - Area (ha)	177,820	602,086	98,654	271,851	163,358	2,425	1,316,193
Crops - Total crops (including cereals and other crops, hay, silage and horticulture) - Area (ha)	143,157	431,530	103,852	236,262	168,420	1410	1,084,631
Crops - Total horticulture - Area (ha)	**33,048**	**3,644**	**409.84**	**14,490**	**17,638**	**486**	**69,716**
Fruit and nuts - Total area (excluding grapes) (ha)	26,279	2,096	112	2,430	16,372	473	47,762
Fruit and nuts - Grapes - Total – Total area (ha)	108	827			221		1156
Fruit and nuts - Orchard fruit and tree nuts - Total area of fruit and nut trees (ha)	24,259	1,309	70	2,150	5,182	112	33,082
Fruit and nuts - Plantation fruit - Bananas - Area (ha)	18	7	14	7	10,684	346	11,076
Fruit and nuts - Plantation fruit - Pineapples - Area (ha)	1,338	770	23	234	26		2,391
Nurseries, cut flowers or cultivated turf - Total area (ha)	527	75	132	83	224		1,041
Cultivated turf - Area (ha)	228	28	94	48	102	0	499
Nurseries or cut flowers - Area (ha)	300	46	38	35	122	0	542
Vegetables - Total - Area (ha)	6,665	123	89	10,283	962	21	18,142

* NRM boundaries do not exactly match GBR catchment areas.

Source: ABS (2022a)

Appendix F. ABARES horticultural areas by catchment and ALUM category 2013-17

ALUM	Catchment	Burnett Mary	Fitzroy	Mackay Whitsunday	Burdekin	Wet Tropics	Cape York	Grand Total
3.4.0	Perennial horticulture	483	17	109	19	52	113	792
3.4.1	Tree fruits	212	8		5	11	62	298
3.4.2	Olives	169	5					174
3.4.3	Tree nuts	140						140
3.4.5	Shrub berries and fruits	13						13
3.4.6	Perennial flowers and bulbs	3						3
3.4.8	Citrus	25						25
3.5.0	Seasonal horticulture	5				6	34	45
4.4.0	Irrigated perennial horticulture	1,049	350	111	195	692	24	2,419
4.4.1	Irrigated tree fruits	5,672	1,262	311	4,118	19,493	462	31,318
4.4.2	Irrigated olives	197	2		4			203
4.4.3	Irrigated tree nuts	11,258	500	145		96		11,998
4.4.4	Irrigated vine fruits	400	2			98		499
4.4.5	Irrigated shrub berries and fruits	1,438	1,072	7	425	60		3,002
4.4.6	Irrigated perennial flowers and bulbs	3						3
4.4.7	Irrigated perennial vegetables and herbs	42						42
4.4.8	Irrigated citrus	4,354	1,534	0	26			5,915
4.4.9	Irrigated grapes	519	1,366		33			1,918
4.5.0	Irrigated seasonal horticulture	6,257	724	237	7,947	524		15,688
4.5.1	Irrigated seasonal fruits	219			297			516
4.5.2	Irrigated seasonal flowers and bulbs	38				7		44
4.5.3	Irrigated seasonal vegetables and herbs	2,478		506	4,234	506		7,723
4.5.4	Irrigated turf farming	241	74	99	249	86		749
5.1.0	Intensive horticulture			13	7	147	7	174
5.1.1	Production nurseries	92	46	38	20			196
5.1.2	Shadehouses	166		1	24	24		215
5.1.3	Glasshouses	91				26		117
5.1.4	Glasshouses - hydroponic	4		1		2		7
5.1.5	Abandoned intensive horticulture	3		6	10	3		21
	Grand Total (Ha)	35,569	6,960	1,583	17,612	21,830	701	84,254

"This workbook contains the data for 'Catchment scale land use profile dashboard - Natural Resource Management regions'. It reports on the area of land use by Natural Resource Management regions (2020). The date of mapping of land uses varies from 2008 to 2019.

The Natural Resource Management (NRM) regions were projected into Australian Albers and rasterised to 50 metres using ArcMap version 10.6 tool Feature to raster. The raster was then combined with the land use 50 metre raster data and exported to the worksheet (ABARES, 2021)."

Source: ABARES, (2021)

Appendix G: Major horticultural zones

Table 6: Main horticultural tree areas per catchment (December 2021)

No. of River Basins	Catchment	Macadamia (ha)	Avocado (ha)	Citrus (ha)	Mango (ha)	Total (ha)	%
5	Burnett Mary	15,622	3,755	3,785	777	**23,939**	70%
6	Fitzroy	460	26	1,480	507	**2,473**	7%
4	Mackay Whitsunday	125	1	6	147	**279**	1%
5	Burdekin		9	36	3,051	**3,096**	9%
8	Wet Tropics	90	2,723	462	1,069	**4,344**	13%
7	Cape York		62		18	**80**	0%
35	**Grand Total**	**16,297**	**6,576**	**5,769**	**5,569**	**34,211**	**100%**
	% of 2010/11	142%	134%	97%	83%	**118%**	

Table 7: Tree areas sorted by GBR river basin.

River Basin	Catchment	Macadamia (ha)	Avocado (ha)	Citrus (ha)	Mango (ha)	Total (ha)	%
Burrum	Burnett Mary	5,425	2,209	40	180	**7,854**	23%
Burnett	Burnett Mary	2,532	891	3,493	287	**7,204**	21%
Kolan	Burnett Mary	3,950	149	159	34	**4,293**	13%
Barron	Wet Topics	55	2,462	421	976	**3,913**	11%
Mary	Burnett Mary	2,661	364	87	147	**3,259**	10%
Fitzroy	Fitzroy	457	21	1,476	217	**2,170**	6%
Haughton	Burdekin		3	4	1,467	**1,473**	4%
Baffle	Burnett Mary	1,053	141	5	124	**1,323**	4%
Don	Burdekin			3	1,027	**1,030**	3%
Others	Various	164	273	81	1,089	**1,606**	5%
	Grand Total	**16,297**	**6,513**	**5,769**	**5,547**	**34,126**	**100%**

Note: While tree crops are planted in every catchment, there are only 9 of the 35 river basins that hold a substantial number of plantations. As can be seen above, 4 of the top 5 are situated in the Burnett-Mary catchment. Green shaded cells include a crop area over 1,000 ha.

Source: Sheppard (2021)

Table 8: Hort360 Reef certification audit planner, indicating major vegetable and pineapple areas.

Sub Catchment	Issue	Commodity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Black	DIN & Fine sediment / PP/ PN	Pumpkin, Watermelon, Mango, Pineapples												
Don	DIN & Fine sediment / PP / PN	Corn-Sweet, Tomato, Mango												
Haughton	DIN & Fine sediment / PP / PN	Beans, Corn-Sweet, Potato, Mango,												
Burnett	DIN & Fine sediment / PP / PN	Potato, Sweet Potato, Avocado, Macadamia, Mandarin, Pineapple												
Burrum	DIN & Fine sediment / PP / PN	Beans, Capsicum, Pineapple												
Mary	DIN & Fine sediment / PP / PN	Beans, Macadamia, Pineapple												
Waterpark	DIN & Fine sediment / PP / PN	Lime, Mango, Pineapple												
Fitzroy (inc. Calliope)	Fine sediment / PP/ PN & DIN	Sweet Potato, Macadamia, Mango, Herbs												
Barron	Fine sediment / PP / PN & DIN	Potato												
Herbert	Fine sediment / PP/ PN & DIN	Potato												
Mulgrave Russell	Fine sediment / PP/ PN & DIN	Corn - Sweet												

DIN – Dissolved Inorganic Nitrogen, PP – Particulate Phosphorous, PN – Particulate Nitrogen

Most likely audit month	
Potential audit month	

Source: Growcom (2018)Source: ABS (2022a)

Appendix H. Queensland Gross Value of Production (2020/21) to commodity level in NRM Reef Catchments

Product	GVP ($) 2020/21	% of Horticulture	% in scope	Area (ha) 2020/21	$/ha
Bananas#*	$598,287,886	25%		11,076	$ 54,015
Citrus#*	$296,040,409	13%	18%	5,480	$ 54,018
Other vegetables	$207,360,266	9%	12%	2,979	$ 69,599
Macadamias*	$156,671,896	7%	9%	15,482	$ 10,120
Other fruit and nuts*	$157,670,311	7%	9%	1,625	$ 97,036
Avocados#*	$146,713,191	6%	9%	6,187	$ 23,711
Sweet Corn	$114,673,908	5%	7%	4,094	$ 28,012
Tomatoes	$101,390,471	4%	6%	1,198	$ 84,639
Potatoes	$74,605,648	3%	4%	2,325	$ 32,090
Capsicums	$70,877,798	3%	4%	1,486	$ 47,698
Nurseries	$70,409,231	3%		268	$ 262,966
Mangoes*	$69,379,150	3%	4%	5,270	$ 13,166
Beans	$68,975,175	3%	4%	4,067	$ 16,960
Melons (watermelon, rock & cantaloupe)	$63,487,824	3%	4%	2,283	$ 27,809
Strawberries	$34,011,544	1%	2%	251	$ 135,504
Grapes	$33,727,889	1%	2%	1,156	$ 29,174
Pineapples	$30,553,700	1%	2%	2,391	$ 12,780
Pumpkin	$17,542,194	1%	1%	1,009	$ 17,394
Herbs (including basil, coriander and parsley)	$15,572,010	1%	1%	124	$ 125,564
Cut flowers	$14,372,869	1%		274	$ 52,416
Turf	$11,834,958	1%	1%	499	$ 23,702
Cucumbers	$3,651,388	0%	0%	80	$ 45,768
Mushrooms	$2,584,515	0%	0%	2	$ 1,179,849
Broccoli	$887,977	0%	0%	57	$ 15,664
Lettuces and Cabbages	$704,727	0%	0%	26	$ 26,939
Carrots	$620,654	0%	0%	15	$ 40,672
Onions and Cauliflowers	$208,642	0%	0%	12	$ 18,096
Total Horticulture (GBR)	$2,362,816,231	100%	100%	69,716	$ 33,892
Total Broadacre & Hay	$1,725,931,622	GBR Hort. contribution		1,014,915	$ 2,328
Total Cropping	$4,088,747,855	58%		1,084,631	$ 1,591
Total Livestock	$2,907,805,271	81%			
Total Agriculture (GBR)	$6,996,553,126	34%			
Horticulture (all Qld)	$3,731,088,815	63%		105,767	$ 35,276
Horrticulture (Australia)	$14,729,095,029	16%		512,624	$ 28,733

Cape York and Wet Tropics NRMs include some production from areas outside of GBR catchments, affecting mainly bananas, citrus and avocadoes. It is unlikely that this would affect their position in the top five crops in terms of value.

* These areas are estimated as 95% of ATCM figures, as ABS only records tree numbers, not areas.

Source: ABS (2022a)

Appendix I: Horticulture water quality risk framework 2017-2022

Soil management (weighting)	**Relative water quality risk**			
	Lowest risk (A)	**Moderate – Low risk (B)**	**Moderate risk (C)**	**High risk (D)**
	Innovative	Best practice	Minimum standard	Superseded
Controlling runoff using buffers (5%)	Buffers in place, these provide good protection of waterways at ALL times OR Not applicable.	Buffers in place, farm run-off is managed prior to any waterway or wetland in the majority of instances.	Buffers in place but concentrated flow occurs.	There are no buffer zones on the property and waterways receive run-off from productive areas.
Fallow management (35%)	Fallow cropping / promotion of ground cover conducted at all times to provide full protection.	Crop residue retained during fallow period/grassed inter-rows maintained to reduce losses.	Limited soil protection practices in place for fallow periods with run-off evident/ weedy fallow / minimum till bare fallow.	No soil protection measures in place for fallow periods/ cultivated bare fallow.
In-field erosion control (20%)	Crops are planted across slope with regular spaced wide vegetation strip cropping.	Crops are planted down slope with regular spaced vegetation strip cropping.	Crops are planted across slope with irregular spaced vegetation strip cropping.	Crops are planted down slope with no other strategies in-place.
Inter-row management (25%)	Inter-rows are managed with ground cover (selected plants species) OR Not applicable.	Inter-rows are managed with ground cover (opportunist plants).	Inter-rows are bare but not cultivated.	Inter-rows are cultivated.
Roadway and headland maintenance (10%)	Roadways and headlands are strategically designed, constructed and maintained to minimise erosion.	Roadways and headlands are maintained with minimal erosion issues.	Minimal maintenance of roadways and headlands occurs and erosion issues remain.	Roadways and headlands are not maintained and erosion is an issue.
Sediment traps (5%)	Not applicable.	Structures that collect sediment are of sufficient size and strategically located. These are working effectively and maintenance is carried out OR not required.	Structures that collect sediment are of sufficient size and strategically located but maintenance is an issue and sediment continues to be lost.	No structures that collect sediment are in place and sediment loss is an issue.

Pesticide management (weighting)	**Relative water quality risk**			
	Lowest risk (A)	**Moderate – Low risk (B)**	**Moderate risk (C)**	**High risk (D)**
	Innovative	Best practice	Minimum standard	Superseded
Calculating pest and crop chemical requirements (30%)	Using own recorded crop monitoring results, action thresholds and labelled rates in line with crop monitoring consultant recommendations/implementation of Integrated Pest Management practices.	Using own recorded crop monitoring results, action thresholds and labelled rates.	Follow chemical / fertiliser supplier recommendations.	Follow other grower advice and / or calendar applications regardless of weather conditions.
Reducing chemical loss to runoff and drift (30%)	Applied at times of low risk using low drift nozzles and low volume applicators in conjunction with wind breaks and recorded weather data.	Spray and OR incorporate at times of low risk.	Spray when opportunity arises regardless of need.	Spray during high risk times.
Integrated Pest Management (IPM) (40%)	A full complement of Integrated Pest Management practices are implemented with minimal pesticide usage.	Have implemented a number of Integrated Pest Management practices but still want to reduce pesticide use further.	Use some Integrated Pest Management strategies. The plan is to move towards reducing chemical usage but has not been implemented.	No Integrated Pest Management used - full chemical use on a calendar basis regardless of need.

Nutrient management (weighting)	**Relative water quality risk**			
	Lowest risk (A)	**Moderate – Low risk (B)**	**Moderate risk (C)**	**High risk (D)**
	Innovative	Best practice	Minimum standard	Superseded
Soil testing (10%)	Frequent soil testing (more than once per year) to fulfil nutrient budgeting requirement across entire farm.	Soil tests completed annually across entire farm.	Infrequent soil testing conducted (2 years or more between tests).	No soil testing conducted.
Leaf testing (10%)	Leaf tests conducted at strategic crop stages in line with nutrient budgeting across entire farm.	Leaf testing completed annually across entire farm.	Infrequent leaf analysis conducted (once every few crops or crop cycles).	No leaf testing conducted.
Nutrient budgeting and recording (30%)	If available, industry recognised software package (Avoman), at paddock scale, based on soil tests, yield data and other sources of nutrient.	Grower developed spreadsheet, sometimes at individual paddock scale, using soil tests and removal calculators.	Nutrient budgeting is paper based at whole farm scale via soil testing.	No nutrient budgeting or recording conducted.
Fertiliser application method (40%)	Various fertiliser application methods used (fertigation, incorporation and / or foliar) with automated fertigation being dominant.	Various fertiliser application methods used (fertigation, incorporation and / or foliar) in accordance with weather conditions.	Fertiliser is surface applied - mixture of broadcast and banding.	Fertiliser is surface applied - broadcasting fertiliser spreader.
Calculating fertiliser rates (10%)	Application rates based on frequent soil and leaf testing using a nutrient budget on a block by block basis.	Application rates based on industry approved nutrient monitoring program.	Application rates based on limited testing information / supplier recommended rates.	Historical application rates applied across entire farm.

Water management (weighting)	**Relative water quality risk**			
	Lowest risk (A)	**Moderate – Low risk (B)**	**Moderate risk (C)**	**High risk (D)**
	Innovative	Best practice	Minimum standard	Superseded
Irrigation scheduling (30%)	Regular use of objective tools to modify irrigation applications.	Intermittent use of objective tools.	Subjective tools used.	Scheduling tools not used.
Matching irrigation interval and volume to crop requirements and soil limitations (50%)	Automated irrigation system, application rate suited to crop stages and soil type.	Manually operated irrigation system, application rate suited to crop stages and soil types.	Irrigation application rates vary with crop stage only.	Same strategy is used across whole farm to calculate irrigation interval and volume.
Water reuse (20%)	Full water reuse. Water quality tests completed regularly OR No opportunity.	Full water reuse / no water quality testing.	Water reused on a limited basis with no water quality test conducted.	No water reuse.

Source: Australian and Queensland Governments (2020a)

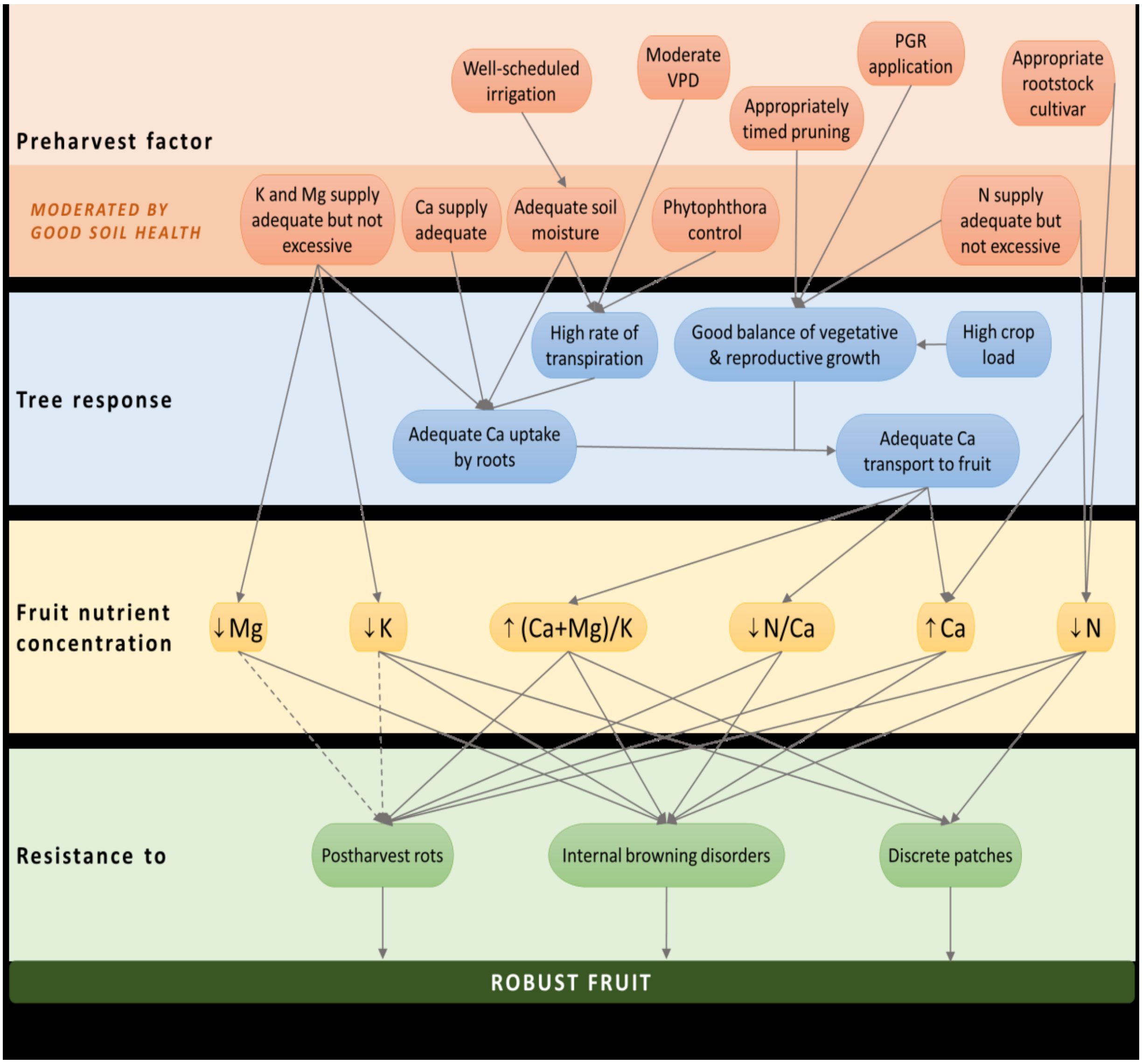
Appendix J: Study sites with reported water quality impacts measured under field or experimental conditions, according to commodity type and Natural Resource Management region in the Great Barrier Reef catchment.

Commodity	NRM region	Location	Years	Type	Measured	Publication
Vegetables	Burnett Mary	Alloway	2010-2011	Field	Sediment (S), Nutrients (N), Runoff quality (R), Deep Drainage (D)	Nachimuthu et al. (2017)
Vegetables	Burnett Mary	Not Recorded	2005-2007	Field	D	Stork et al. (2007)
Macadamia	Burnett Mary	Bundaberg	2005-2006	Field	S, N, Phosphate (P), R	Stork et al. (2007, 2009, 2012)
Pineapple	Burnett Mary	Yandaran	2019-2020	Field	S, N, P	Australian Pineapples (2019a,b); Griffin (2020a,b)
Pineapple	Burnett Mary	Imbil	1988-1991; 1995-1996	Field	S, R	Ciesiolka et al. (1995); Coughlan and Rose (1997); Palis et al. (1997)
Pineapple	Burnett Mary	Goomboor-ian	1991-1995	Field	S, R, N	Coughlan and Rose (1997); Yu et al. (2000a,b)

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

Source: Soil Catchment and Riverine Process Group, 2022, p. 72-74

Appendix K. Nutrient impacts on quality of avocado fruit.



Note: Dashed lines indicate nutrient has been associated with both increased and decreased defect expression.

Source: Perkins et al., 2020, p. 46

Appendix L: Avocado Association Best Practice Resource Nitrogen application guidelines

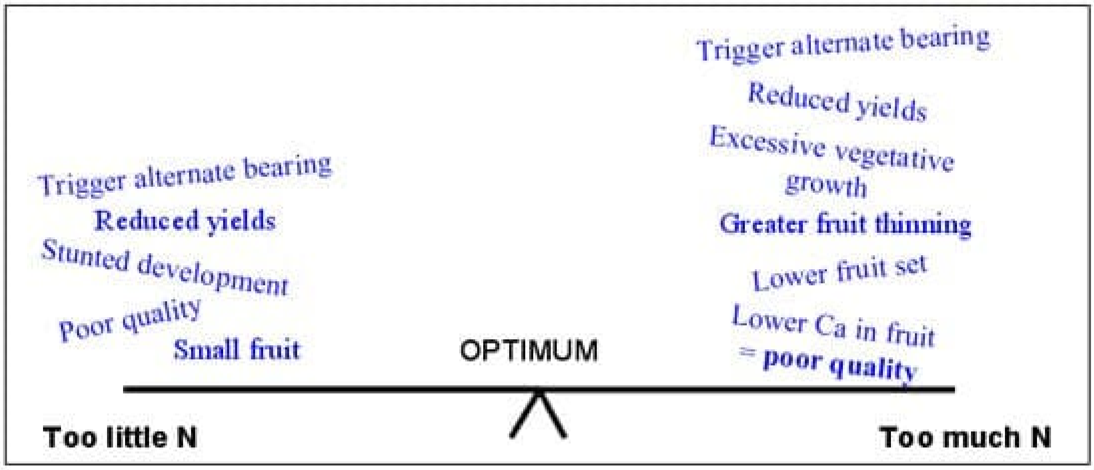
Guidelines for annual nitrogen applications for young and mature trees on a per square metre of canopy basis. Best to split into monthly applications (can be extended to bimonthly through winter)

Tree stage	**Optimum % leaf tissue nitrogen level**	**Elemental nitrogen per square metre of canopy area per year**	**Example using Nitrophoska Perfekt + urea (total grams per square metre of canopy area per year)**
First year in the ground	2.6 – 3.0% N (2 – 2.4 for Fuerte & Sharwil)	100 g	270 g Nitrophoska + 130 g urea
Young tree, no crop yet	2.4 – 2.8% N (1.8 – 2.2 for Fuerte & Sharwil)	70 g	190 g Nitrophoska + 90 g urea
Young tree, first crop	2.2 – 2.6% N (2.0 – 2.4 for Fuerte & Sharwil)	40 g	110 g Nitrophoska + 50 g urea
Mature, bearing	2.2 – 2.6% N (2.0 – 2.4 for Fuerte & Sharwil)	14 g	40 g Nitrophoska + 20 g urea

The following are factors that should be considered to adjust the above guidelines for mature trees:

- Leaf tissue nitrogen level (up to 50 per cent more for very deficient levels or 50 per cent less for very high levels).
- Appearance of the tree (yellow, pale green, dark green).
- Amount of nitrogen already in the soil.
- Amount of recycling happening through leaf fall.
- Soil texture (higher rates, up to 20 per cent more, for lighter soils).
- Tree health (up to 30 per cent less for trees severely affected by Phytophthora root rot).
- Degree of leaching (increase rate, up to 20 per cent, after significant rainfall events).
- Crop load (higher rates, up to 50 per cent more, for heavy crops).
- Two crops on the tree for part of the year, for example Western Australia, Sunraysia (about 10 per cent higher rates).
- Higher rates may be required in conjunction with the use of plant growth regulators e.g., Sunny® (refer to manufacturers guidelines) variety (Sharwil and Fuerte require about 20 per cent less nitrogen).

Nitrogen must be managed carefully to achieve the correct balance because the rate and timing of nitrogen applications can significantly affect fruit yield and quality. The effects of either too little or too much nitrogen are summarised in the following diagram.



The nitrogen 'balance'

Timing of nitrogen applications

In the past nitrogen applications were restricted to autumn time (particularly for 'Fuerte'), now the trend is to apply small amounts throughout the year preferably at monthly intervals (can be extended to bimonthly through winter) with higher rates in autumn and lower rates in winter. In spring during flowering, fruit-set and early fruitlet development make sure not to overdose because this can trigger vegetative growth at the expense of yield and fruit quality.

This is the advice given to avocado growers in the Best Practice Resource section of the Avocados Australia website, which is a member only access, and is reproduced here by permission.

A visual representation of the requirement to find the right balance yield and fruit quality by considering the timing and rate of nitrogen application is shown below.

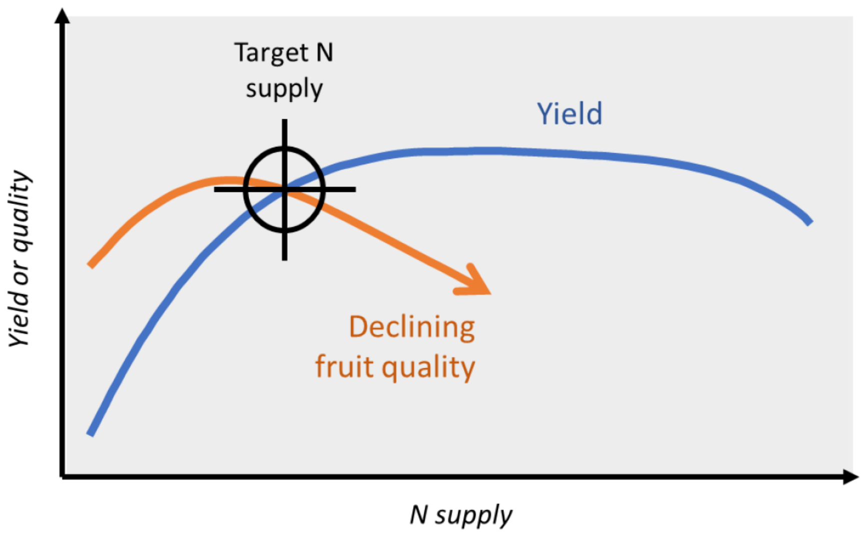


Figure 1: Nitrogen supply management for balance between avocado fruit yield and quality.

Source: Perkins et. al., 2020, p. 9