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A horizon scan for improving pesticide management and governance in the great barrier reef catchment

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The current policy environment for improving catchment pesticide water quality entering Australia's Great Barrier Reef lagoon is based around Scientific Consensus Statement processes, which utilise systematic scientific literature reviews to develop policy recommendations. This paper modifies consensus approaches to incorporate structured horizon scanning into future policy needs facing farming sustainability in the Great Barrier Reef watershed. Horizon scanning identified several emerging challenges, and opportunities, spanning diverse themes including: a dynamic pesticide regulation and accessibility future; the need for better policy recognition of whole-of-farming system sustainability considerations; little consistency in integrated pest management frameworks across industries; technology; and increasingly complex stakeholder engagement needs. Several of the highest priority issues identified received no, or only cursory, attention in more backward-looking Scientific Consensus Statement outputs. These issues need careful integration into future Great Barrier Reef policy initiatives to maximise impact of already substantial government and industry investment in improved farming practice change.

KEYWORDS

water quality, sustainable agriculture, transdisciplinary, integrated pest management, agroecology, pesticide regulation, participatory policy, ecosystem services

1 Introduction

Water quality is broadly recognised as a key risk to the long-term resilience of Australia's Great Barrier Reef (GBR) World Heritage Area (Brodie et al., 2012; Waterhouse et al., 2024). Pesticides (along with suspended sediments and dissolved inorganic nitrogen) have been acknowledged as a risk to GBR ecosystems since the 1990s, precipitating extensive pesticide monitoring and policy responses in the GBR marine environment and associated catchments. Sugarcane areas are the largest contributor to end-of-catchment pesticide concentrations (dominated by photosystem II (PSII) herbicides), with broadacre cropping, horticulture, banana growing, grazing, forestry, and urban areas also contributing in certain catchments. Pesticides have been detected in GBR waters, sediments and biota since the 1990s (Haynes et al., 2000; Negri et al., 2024). Recent monitoring programs have consistently identified over 70 pesticides and their transformation products in >99% of water samples collected across end-of-catchment waterways, palustrine wetlands (e.g., vegetated swamps) and in estuarine and nearshore marine habitats. Concentrations of pesticides (typically in mixtures) are greatest in wetlands, followed by end-of-catchment then marine locations, with concentrations. and risk, decreasing with greater distance from river mouths (Negri et al., 2024). Previous monitoring-modelling has suggested modest, but steady improvements toward end-of-catchment PSII herbicide load-based reduction targets (Waterhouse et al., 2017), although increasing trends in concentration and/or risk have been recently documented for pesticides, in some GBR ecosystems (Warne et al., 2022; Taucare et al., 2022). The Great Barrier Reef catchment area (GBRCA) has been a dynamic pesticide policy environment, with the imposition of regulations on certain chemical use specifically targeting key GBRCA agricultural industries such as sugarcane. The GBRCA represent one of the few areas of Australia where potential pesticide impacts, and the value of the environment, have resulted in additional formal regulation on regional pesticide usage, above and beyond national frameworks (APVMA, 2012).

Scientific Consensus Statements (SCS) are formal, periodic (4-5 yearly) review processes used by federal and state policymakers as key evidence-based documents for monitoring and managing GBR water quality (Waterhouse et al., 2017; 2024). The SCS process guides the design, delivery and implementation of the Australian and Queensland government's Reef 2050 Water Quality Improvement Plan (Commonwealth of Australia, 2023), defining management objectives, targets, funding and spatial management priorities for improving the quality of the water that enters the Great Barrier Reef from the adjacent catchment. The most recent SCS process includes several changes to previous iterations to ensure best practice standards for the synthesis of evidence for environmental policy/management, and to increase transparency and rigor of syntheses; namely, a systematic, evidence-based review of published scientific literature, followed by additional expert peer review (Pineda et al., 2022; Waterhouse et al., 2024). By its very nature, SCS philosophy tends to be inherently backward-looking (i.e., finding consensus or 'hindcasting'), with little deliberate or systematic effort made to produce or anticipate outlooks of the future (in fact excluding incipient or anecdotal information).

The latest SCS highlights some notable changes to pesticide risk appraisal, targets and progress tracking for the GBRCA, that warrants increased recognition of the need for broader and more integrated long-term policy planning surrounding pesticide management (Davis et al., 2024). The most far-reaching modification under the current Reef 2050 Water Quality Improvement Plan 2017–2022, is the shift from previous 60% end-of-catchment load reduction targets for a suite of 'priority' photosystem II herbicides (PSII; diuron, ametryn, atrazine, hexazinone, simazine, tebuthiuron) to the new aim of achieving pesticide concentrations at GBRCA river mouths that protect at least 99% of aquatic species (The State of Queensland, 2018). Reef Plan pesticide focus has, accordingly, expanded substantially, now including a much broader, and expanding, range of 'priority' pesticides (a combination of herbicides, insecticides and soon to include fungicides), and a more integrated appraisal of the risk of pesticide mixtures, applied to end-of-catchment wet season concentration data (The State of Queensland, 2018; Warne M. St. J. et al., 2023). Much of the historical GBR pesticide policy agenda surrounding intensive agriculture largely focused on sugarcane, which accounts for ~1% of total GBR catchment area (Lewis et al., 2021). These more integrated targets now expand policy focus onto a much broader suite of pesticides, but also GBRCA agricultural industries, particularly bananas (~0.1% land area), horticulture (~0.2% land area), and irrigated and dryland broad-acre cropping (cotton, grains; ~2.2% land area).

Policymakers and practitioners in many fields, particularly environmental management, often make decisions based on limited evidence, dealing with issues that appear unexpectedly, but that with hindsight, were often foreseeable (Sutherland and Woodroff, 2009; Bengston, 2013). Pesticide policy changes are particularly prone to unintended, or even perverse, on-ground outcomes (Davis et al., 2014; Finger, 2018). A solution to the problem of failure to anticipate such scenarios are forms of foresight research such as routine Horizon Scanning (HS), broadly defined as the systematic search for emerging trends, issues, opportunities, threats, and events, which can facilitate proactive responses by scientists, managers, and policymakers (Sutherland and Woodroff, 2009). The benefits of formal horizon scanning have seen its increasing recent application in variety of catchment, marine and coastal water quality-landuse policy and planning scenarios (Pérez-Jvostov et al., 2020; Orr et al., 2022; Herbert-Read et al., 2022). This paper aims to provide a working example of simple extension of current SCS processes into an additional Horizon Scanning domain. It identifies emerging regulatory, scientific, technological, and socioeconomic issues that are very likely to impact the effectiveness and implementation of pesticide policy and farming practices in GBRCA agricultural sectors within the next 5–10 years. The goal in highlighting these issues is to raise awareness, encourage scrutiny and provide direction for more forward-looking research, technological, and policy innovation agendas.

2 Materials and methods

While a range of Horizon Scan strategies are available (Sutherland and Woodroof, 2009; Bengston, 2013), the Horizon Scan strategy was developed to be repeatable, transparent, and compatible with existing SCS processes. A modified, two-step, initial 'Literature Search/state-of-science' approach followed by a subsequent 'Expert Workshop-Interview' method of expert consultation, voting and anonymity was utilised (Sutherland and Woodroof, 2009). SCS pesticide management chapter authors firstly used the same systematic literature review search strings and outputs from SCS chapter development (Davis et al., 2024) to broadly screen peer-reviewed literature to generate an initial list of potential future issues facing GBR pesticide management (with short synopses of each issue). Several of the proposed issues had already been identified and specifically discussed in SCS outputs (i.e., pesticide resistance management challenges, unknown toxicity of pesticide mixtures etc.), with the rest receiving no, or very cursory, attention in final SCS literature (Table 1). Specific search strings (SCOPUS, Web of Science) and systematic literature review processes are outlined in Supplementary Material and references (Davis et al., 2024; Waterhouse et al., 2024). A list of 23 initial potential issues and their synopses (in a spreadsheet; summarised in Table 1) were circulated to a broader group of 17 pesticide and weed researchers, senior agronomists and extension experts currently

TABLE 1 The final 29 future policy, extension and research issues facing GBR pesticide management identified from Horizon Scanning. Questions are grouped and discussed under five research themes.

Pesticide management question-issue	Rank
Theme: 3.1 pesticide regulation and accessibility: uncertain futures for many pesticides	
Regulatory authority registration changes limiting allowable uses (i.e., the impacts of current and future APVMA chemical reviews)	1
'Generic' pesticide product availability changing future farmer usage patterns (i.e., cheaper products coming onto market following specific pesticide active ingredients coming off patent)	7
Manufacturer removal of pesticides from market	22[#]
Registration of new pesticide products to market	27
3.2 'whole-of-farming system' considerations and the need for 'systems-oriented' policy	
Interactions between water quality management outcomes and impacts on other major environmental issues (greenhouse gas emissions, water use efficiency, soil health, microplastics etc.)	2
Potential farming sustainability and water quality tensions or trade-offs across different water quality pollutants (i.e., relative environmental impact of pesticides vs. nutrients vs. sediments)	3
Pesticide resistance risks emerging from water quality BMP recommendations (i.e., increased use of knockdown herbicides)*	10
Pesticide resistance management strategies increasing other water quality risks (increased use of tillage and residual herbicides in weed control to slow weed resistance evolution)*	12
Lack of recognition in reef plan policy around interactions between pollutants (i.e., synergistic or additive effects between sediments-pesticides)	15
Groundwater interactions in pesticides*	17
Implications of other farming system interactions for affecting pesticide use or loss (minimizing need for pesticide application through improving soil health, nutrient use efficiency, crop vigor etc.)	19[#]
Emergence of new crop pests (novel weeds and insects)	23
Climate change impacts (changes to weed species' ranges, crop-climate changes)	26
Understanding of fungicide risks to water quality*	29
3.3 stakeholder extension challenges; gaps, shifting goalposts and different industries	
Reseller-advisor gaps in pesticide policy and extension environment (i.e., the agrochemical re-sellers and spraying contractors making pesticide recommendations to farmers)	4[#]
Unanticipated toxicity of 'alternative' (non-PSII) pesticides in farming BMP recommendations*	5
Lack of knowledge around pesticide mixtures and their toxicity (for farmers, extension advisors, agro-chemical re-sellers)	6
Lack of trained extension staff across industries (in terms of knowledge around pesticide ecotoxicity etc.)	8[#]
Stakeholder extension challenges associated with policy shifts from PSII load-based to 99% ecosystem protection targets at end-of-catchment	13
Lack of economic appraisal of many 'pesticide best management' practices compared to older practices?	16[#]
Transferability of edge-of-field paddock runoff-water quality data to 'end-of-catchment' improvements*	18
New 99% ecosystem protection targets capturing a much broader range of commodities (horticulture, broad-acre cropping etc.)*	20
Increasing 'science skepticism' and a contested science-policy landscape?	28[#]
3.4 technology- current constraints and future opportunities	
Lack of industry consistency in pesticide application standards (spray rig setup, calibration practices etc.)	9[#]
Technological opportunities to reduce pesticide use (genetic, precision application, machine learning)*	11
Other currently overlooked non-pesticidal opportunities to manage pest pressures?	24
3.5 an uncertain future for integrated pest management in the GBR catchments	
Neglected IPM implementation or opportunities across different GBRCA commodities	14
Minimal reef plan BMP focus on broader scale practices for reducing pesticide application (area-wide management, surveillance, economic thresholds etc.), and overt focus on paddock-scale management*	21

(Continued on following page)

TABLE 1 (*Continued*) The final 29 future policy, extension and research issues facing GBR pesticide management identified from Horizon Scanning. Questions are grouped and discussed under five research themes.

Pesticide management question-issue	Rank
Cultural controls as a non-pesticidal pest control measure (planting density, row spacing etc.)*	25

*Indicates issues that received detailed discussion in final Scientific Consensus Statement literature review outputs (Davis et al., 2024).

#Indicates issues not captured in initial list provided to participants, but emerging from subsequent 'wildcard' responses.

working across government, industry and non-government organisations within the GBRCA (but all outside the SCS process).

The group included diverse commodity (sugarcane, bananas, horticulture), research (weed agronomy, pesticide efficacy, Integrated Pest Management (IPM) development), and farming extension and support (government-public and private sector extension staff) mandates across a range of GBRCA agricultural systems. >80% had tertiary educational qualifications, and all respondents had 20+ years of experience in the region, and collectively live-work across most of the major GBRCA agricultural regions (Mackay-Whitsunday, Burdekin, Herbert, Tully-Johnstone, Russell-Mulgrave, Cairns, Mossman etc.) and wet and dry-tropical (i.e., irrigated and non-irrigated) cropping zones.

Participants prioritised issues by independently and confidentially scoring each of the initial 23 policy, practical and research issues from 1 to 100 (low–high) according to two main criteria: its potential to impact pesticide management and policy (whether positively or negatively) over the next 5–10 years, and the novelty of the issue. All participants were also provided a conceptual model for pesticide management from the SCS process as a prompt (Supplementary Figure S1), but also to assist in framing scope of issues for consideration. Participants were encouraged to add notes or detailed context to key issues in the spreadsheet and offered opportunity to identify up to two additional topics not identified in the initial provided screen (i.e., 'wildcard' issues; Bengston, 2013). A smaller series of seven additional 'wildcard' topics emerged from collective respondent feedback (Table 1), which were added to the initial issues list, re-circulated, and re-scored by respondents. Issue scores were subsequently converted to ranks, and the median rank of each issue was calculated. A final synthesis of ranked issue scores and collated discussion was sent back to all participants for any final comments and feedback.

Well-developed horizon scanning should encourage researchers, policymakers, and practitioners to engage in joint fact-finding, an exercise through which stakeholders with potentially diverse interests collaboratively identify, define, and answer scientific questions that hinder development and implementation of effective policies (Neve et al., 2018). Our tailored, two-stage method utilises the more structured 'literature search/state-of-science review' scanning approach for published threats and opportunities from peer-reviewed evidence, but complemented with the subsequent credibility of 'expert workshop' type approaches (using teams of on-ground practitioners to suggest possible issues not yet, or poorly captured, in more backward-looking published research literature; see Sutherland and Woodroff, 2009). Utilising existing formal SCS literature review outputs value-adds to existing SCS investment and could provide a relatively simple working template for future HS modifications to SCS approaches.

3 Results

Sixteen of the 17 initially approached experts provided detailed, ranked prioritisations and feedback to the HS process. There were inevitable interactions and overlaps emerging across many issues. Accordingly, specific issues are not presented in rank order but are instead grouped into five broad themes with ostensibly distinct policy and research considerations (and the highest ranking issue within each theme forming the basis of subsequent discussion): pesticide regulation and accessibility (Section 3.1); whole-of-farming system considerations (Section 3.2); stakeholder extension and engagement (Section 3.3); technological opportunities and constraints (Section 3.4); and Integrated Pest Management (IPM; Section 3.5). Ranks from final scoring of individual issues, and their thematic groupings are presented in Table 1.

3.1 Pesticide regulation and accessibility: uncertain futures for many pesticides

3.1.1 Regulatory changes to permitted usage of the currently registered pesticide resource

This issue consistently ranked as highest significance in most expert responses across sugarcane, horticulture, bananas and broad-acre cropping (Table 1), prompted by current regulatory authority reviews of multiple pesticides, and the even broader range noted as nominated for future re-evaluations (see APMVA, 2025). While the speed of these regulatory reviews is sometimes protracted (Brodie and Landos, 2019), much of the current GBRCA pesticide resource is likely to encounter significant regulatory scrutiny, if not direct pressure on accessibility, in next 5–10 years, or even sooner. Multiple HS participants specifically noted the current Australian Pesticides and Veterinary Medicines Authority (APVMA) review of the non-selective herbicide paraquat (APVMA, 2024) as one with the most potentially profound impacts on GBRCA herbicide usage and associated best management practice (BMP) and water quality outcomes in the last 3 decades. Paraquat was noted as a keystone resource in recent farming industry transitions to lower reliance on residual PSII herbicides (see also Davis et al., 2014). Proposed regulatory changes to allowable application rates of paraquat was frequently noted as possibly forcing multiple industries to revert to widespread reliance on residual herbicides, also the 'spiking' of pesticide mixes with higher risk pesticides to increase efficacy, or re-introduction of tillage control of weeds, undermining several decades of government and industry investment in herbicide practice change in GBR catchments. Several of the candidate post-emergent herbicides alternatives likely to fill the paraquat gap (i.e., MSMA) were also noted as having significantly higher environmental risk profiles compared to paraquat in recent 'pesticide decision support tools' (Warne M. S. J. et al., 2023) recently made available to farming industries (at least from a water quality risk perspective).

Recent regulatory requirements for increases to downwind buffer zone requirements were also cited by some respondents as already constraining early (boom applied) knockdown use in some farming systems, with reversions back to residual herbicide usage for early weed control by some farmers, an outcome counter-productive to recent BMP policy objectives. Other Australian and GBR commodities were noted as still grappling with registration withdrawals of insecticide mainstays such as endosulfan (horticulture) and chlorpyrifos (bananas), with research into alternative control techniques (both chemical and non-chemical) remaining a high priority (see Domeniak and Ekman, 2013; Huwer et al., 2015). Potential regulatory changes to fungicides such as mancozeb and chlorothalonil, both critical and widely used resource in managing foliar diseases in crops such as bananas and cucurbits, were also noted as concerning, with few viable alternative control methods currently available to farmers. Government investment in R&D initiatives such as modelling and predicting the likely water quality implications of significant regulatory changes to key pesticides, and specific participatory co-design with industry and advisory-extension networks on developing and promoting the most sustainable, practical best-management practices for farmers would seem logical policy responses to a clearly dynamic pesticide accessibility landscape.

3.1.2 Emergence of generic products or product discontinuation changing usage patterns

Changes to pesticide active ingredient patents and availability of cheaper generic options were highlighted as both a sustainability threat and opportunity by respondents. The market availability of cheaper generic formulations after patent discontinuation was noted as seeing rises in prophylactic use of certain chemicals such as imidacloprid in the GBRCA, an outcome evident in water quality monitoring (Allsopp, 2021; Warne et al., 2022). In contrast, several active ingredients with ostensibly better environmental profiles (e.g., flumioxazin) recently coming off-patent was suggested to provide opportunities for more affordable agrochemical options with lower risk profiles to farmers. Individual manufacturer decisions to discontinue certain controlled release formulations of products (i.e., imidacloprid) due to microplastic contamination concerns were also noted as having potentially significant water quality impacts. This leaves potentially more mobile, and frequently applied, liquid imidacloprid formulations as all that is currently available to industry. Significant recent shifts in regional usage toward other neonicotinoid insecticides (such as clothianidin) in response to manufacturer discontinuation of certain imidacloprid formulations was also noted by several HS respondents.

3.2 'Whole-of-farming system' considerations and the need for 'systems-oriented' policy

3.2.1 The need for GBR policy to recognise farms as holistic management systems

Collated respondent feedback (detail added to participant prioritisations) frequently noted the long-standing GBR water quality BMP purview as somewhat reductive, focusing on, and often compartmentalising individual pollutants (pesticides, suspended sediment, nutrients), with minimal recognition of interactions and potential tensions/trade-offs between specific pollutants and their respective management strategies. Pesticides in many ways encapsulate these trade-offs within a farming system, with shifts in recent decades toward sustainable agricultural practices such as minimum and zero tillage cultivation (addressing soil health and erosive loss) in multiple industries significantly increasing reliance on herbicides for weed control (see Johnson and Ebert, 2000). Similarly, other advocated BMP practices for other elements of the total farming system such as utility of fallow crops (for nutrient and soil health benefits, breaking crop monocycles, income diversification etc.) and wider row spacings for controlled-traffic systems (soil health and sediment management) were often touted by HS participants as requiring additional chemical pest control. Several respondents similarly noted recent experiences with ostensibly negative outcomes from end-of-paddock pesticide concentration results associated with significant improvements to furrow irrigation water use efficiencies (greatly increased edge-of-field pesticide runoff concentrations due to lower dilution effects from significant reductions in tailwater losses). The provided conceptual model was noted specifically by several respondents as treating pesticide management as a separate part of the cropping system, not clearly linked to the broader farming system and other sustainability issues such as nutrient use, soil conservation and water use efficiency. The need for pesticide policy and governance being better embedded within broader natural capital and ecosystem service considerations was a common theme in HS feedback.

3.2.2 The spectre of herbicide resistance

The water quality implications (reintroduction of residual herbicides and tillage) of future management of pesticide resistance emerged as a dominant study focus from systematic SCS literature searches (Davis et al., 2024), particularly in broadacre and horticultural contexts, an outcome paralleled in HS issue ranking. Respondents noted other major industries such as sugarcane were long regarded as somewhat buffered from resistance issues, due to an extensive 'herbicide toolbox' available for weed control and the presence of trash blanket in most sugarcane districts that acts as a physical barrier to many weed species and significantly reduce the reliance on chemical control. The long-term prognosis for this outlook seems increasingly uncertain, with potential reduction of available active ingredients from diverse mode of actions. The importance of ensuring for some advocated broader farming system BMP strategies in sugarcane do not contribute to pesticide resistance (i.e., increased use of glyphosate, desiccation of fallow crops with sub-lethal application of 'knockdown' herbicides below recommended rates) were also highlighted. Specific concerns around the potential for entomological resistance were noted in the sugar industry relying on the use of a single insecticide mode of action such as neonicotinoids to control canegrubs since 2004; and in GBRCA horticulture, where up to 20 crop cycles per year increases need for monitoring for insecticide resistance. Similarly, the registration loss of chlorpyrifos in bananas was noted as reducing chemical mode-of-action diversity options for key bunch pests such as rust thrips

(*Chaetanaphothrips signipennis*), whose short life cycles predisposes them to rapid resistance evolution. Control of symphylans in sugarcane at planting was likewise noted as possibly being reduced to one active ingredient at the conclusion of the current APVMA fipronil review.

3.3 Stakeholder extension challenges; gaps, shifting goalposts and different industries

3.3.1 The chemical advisor, reseller, spraying contractor gap in current pesticide policy

Respondents consistently noted a major challenge to current and future GBR pesticide management policy is the widespread reality that many farmers get their pesticide advice from external sources (spraying contractors or agrochemical resellers), who may have not received the appropriate training related to pesticide water quality risks, and may have other priorities to consider. Respondents noted a significant and widespread shift from public toward private sector (pesticide) extension advice across multiple GBRCA commodities (broadacre, grazing, horticulture and sugarcane), and the specific increasing use of spraying contractors to apply pesticides in key industries such as sugarcane (see also Taylor and Eberhard, 2020). Farmers may incorrectly assume these external 'advisors' have a full understanding of water quality risk considerations. Alternative herbicidal options to higher risk and more familiar chemicals, for example, were noted as available in many cases, but agronomic and environmental considerations to ensure their efficacy may be poorly understood by the external contractors and resellers, either recommending or applying products. Some level of regulatory oversight on pesticide resellers and spraying contractors, or at least periodic requirements for formal 'upskilling', was specifically raised multiple times by respondents. Policy precedents certainly exist in this space, with requirements for pesticide distributors and advisors having to complete both initial, and periodically updated, certification and training to provide customers with adequate, environmental risk-based information at the 'point of sale' becoming increasingly common in many countries (Department of Agriculture, Food and the Department of AgricultureFood and the Marine, 2013; Lefebvre et al., 2015).

3.3.2 Shifting water quality goalposts

While the recent expanded pesticide risk appraisal framework (to % ecosystem protection and greater numbers of pesticides) undoubtedly improves capacity to make ecologically relevant appraisals of pesticide risks in the GBR environment, it was frequently noted as likely giving perception to farmers of 'shifting of goalposts' on the part of government policymakers. Pesticides were the best tracking pollutant under the now superseded Reef Plan PSII load reduction targets (>50% load reduction)4. Recent studies using the new 'Total Pesticide Risk' frameworks indicate ~85% of catchment estimates were achieving >1% ecosystem protection - meaning they did not meet the Reef 2050 Water Quality Improvement Plan's pesticide target for waters entering the GBR (Warne M. St. J. et al., 2023). Responses suggested this could present a significant upcoming challenge for farmer enthusiasm and trust in BMP extension around water quality. The 'Total Pesticide Risk' approach was also noted as complex and confusing to understand for advisors and farmers in multiple industries. The newer, integrated pesticide risk focus also fundamentally changes the on-ground farming 'best management practice' (BMP) environment in industries well-used to load-based targets and BMP recommendations, complicating it in ways that should not be underestimated. A lack of clarity for extension staff and practitioners on the comparative environmental risks posed by herbicide mixtures (see also Davis and Neelamraju, 2019) from different management practices, and linkages to groundwater, were particularly noted as challenges for future policy directives. Retention of traditional pesticide load-based water quality reporting at paddock and broader catchment scales, to complement or provide context to new 'Total Pesticide Risk' frameworks was repeatedly highlighted as an important industry extension-engagement consideration.

3.3.3 Farming is still a business

Fundamental economic drivers were noted by respondents as a dominant, but still largely unappreciated component of farmer decision making around pesticide control options (at least at a policy level). Specific feedback included "I think the scientists and environmentalists always tend to ignore the fact that farming is not a super lucrative occupation for 90% of farmers. Any recommendations should be assessed by economists, as it can put some farming enterprises out of business" or "Growing a crop with the lowest input costs drives most agricultural businesses." The majority of farming businesses in Australian are carrying significant financial debt, so the saying in agriculture - "It is difficult to be green when your bank balance is in the red; this a cold hard reality for most farming businesses". The fear of crop failure, or decreased yields, remains at the forefront of most farmer decision-making, hence they will use proven and trusted methods to ensure that productivity is not compromised. These sentiments are not without merit given the relatively limited number of economic studies noted as available to SCS practice change appraisals of the economic feasibility of farming practice changes (Davis et al., 2024).

3.3.4 Existing extension-advisory capacity and need for new models

Respondents consistently noted a lack of experienced staff and/or extension capacity for targeted extension effort across multiple industries. The capture of a broader suite of agricultural commodities was raised as also introducing possibly unanticipated extension and communication challenges to the current GBR pesticide policy environment. Some GBRCA industries such as sugarcane, with larger land areas, but low profit margins per hectare have relatively egalitarian annual pricing systems set by global markets, and similarly open industry extension and communication networks. More high value per hectare commodities such as bananas and horticulture involve more direct competition between individual farmers (particularly around product quality), with fewer farm advisers, and very different extension, communication networks and intellectual property (IP) considerations in play, particularly regarding farming system innovation and technology.

Over the past few decades government-funded agricultural extension-advisory programs have declined, with private sector agronomists taking up the role of providing farmers with agronomic advice (see Taylor and Eberhard, 2020), particularly in the cotton, horticulture and broad acre industries. Government funding, particularly for public good benefits such as water quality improvement has grown in importance in the last 2 decades, distributing the funding to a range of available service providers (i.e., private agronomy consultants, industry managed organisations, government employees) but little consideration was given to the coordination between these competing service providers to ensure the distribution of clear technical messages to the farming community. A new model is needed to ensure future fundings take into consideration appropriate coordination between now often competing public and private service providers.

3.4 Technology- current constraints and future opportunities

3.4.1 Getting the best out of available technology

A recurrent HS comment was the continuing long-term constraint of ensuring basic pesticide application practices, with many farmers and advisors across multiple sectors in need of upskilling. Respondents noted little recognition of what constitutes 'best management practice' for the key process of applying pesticides to fields, a shortfall noted as evident even in several industry developed BMP programs. Most farming sectors have no clear standards (i.e., limited industry BMP relating to management of spray drift), much application equipment (spray rigs) is functioning poorly, and in some case, inappropriately calibrated, and concepts such as spray capture and spraying efficiency still confusing to many farmers and their advisors. Fundamental baseline data on issues such as spray rig setups (correct nozzles, pressure, Global Positioning System (GPS) cutoff automation for paddock boundaries and buffer zones etc.) was noted as lacking across multiple agricultural industries. For example, recent localised appraisals of the functioning of boom sprayers (one of the most widely used pieces of pesticide application equipment) in specific sugarcane catchments noted a high proportion of deficiencies and inefficiencies in spray rigs in relation to risks to both the environment and operator safety (Sluggett and Keilbach, 2025). Common issues encountered across assessments of spray units included mismatched nozzle and row spacing, boom section and crop layout, and nozzle output and boom height limitations.

Failure to recognise and remediate these fundamental components of pesticide application to the environment, through targeted extension by skilled advisors, was noted as a critical current HS gap, and also one that will undermine policy effectiveness relating to future adoption of precision application technologies. Several respondents that industries "are often good at promoting some new application technology, but not so good in ensuring its effective use, or the benefits of utilising existing, often simpler, equipment effectively". Unless certain fundamentals are addressed, the same behaviours around poor application practices were predicted to continue, and generate limited measurable improvement, regardless of policy efforts. Again, global experiences with similar spray application challenges across industries, and subsequent policy responses (spray equipment standards, mandatory and periodic spray equipment testing requirements in many European counties; Kole and Wehmann, 2024) offer potential policy frameworks for the GBR catchment (see also recommended operational minimum standards in Sluggett and Keilbach, 2025).

3.4.2 Emerging technological opportunities

While cognizant of the need to pursue and develop new technologies, non-pesticidal options for pest control (i.e., weed control using mechanical means (electricity, laser, steam, biocides etc.)) were noted as still extremely difficult to technically and cost-effectively implement in several major industries such as sugarcane. Similarly, 'green on green' weed sensing technologies (Rahimi Azghadi et al., 2024) for precision pesticide application in crops such as sugarcane were also noted as promising, but still not commercially available. But examples of the capacity of Information and Communication Technology (ICT) and digital sustainability transformations to disrupt agricultural practices through rapid, and large-scale farming practice change were also noted. The combination of a recent series of wetter climatic years during typical pesticide application windows, and cheaper drone application options (cf. to traditional helicopter or plane applications) has provided significant on-ground 'proof-of-concept' and widespread impetus to rapid industry uptake. The financial, practical and farming benefits (less machinery access to wet paddocks, timing flexibility) and still largely unexplored potential of drone technology (use of 'softer' herbicides, spectral mapping) were repeatedly cited as a significant sustainability opportunity. Use of fixed wing and helicopter aerial foliar fungicidal applications were noted as increasing in bananas in recent years (cf. to historical on-ground spray rig usage), with drones also noted as a potential opportunity to improve application precision and efficiencies, particularly near farm boundaries or buffer situations.

Constraints also exist here, with respondents noting much government legislation on aerial application and pesticide labelling is struggling to accommodate the introduction and rapid application of drone technology in agricultural settings. Increased R&D investment (spray drift, efficacy, calibration standards etc.) and agri-environmental policy interventions here (equipment and training subsidies for drone operation, better integration of drone technology into current chemical labelling restrictions on 'aerial application') could add considerable 'push-pull' momentum (Möhring et al., 2020) to new technological interventions.

vThe recent Brazilian launch of the first commercial use of transgenic sugarcane expressing *Bacillus thuringiensis* (Bt) proteins to control significant sugarcane borer pests, *Diatraea saccharalis* (F.) (Sakuno et al., 2024) was also noted as an opportunity for GBRCA industries such as sugarcane to similarly reduce reliance on synthetic insecticides. But respondents also noted the sensitivity of some of Australia's international markets to the use of genetically modified (GM) technologies in crops, the laborious and technical challenges of genetic transformation of sugarcane, and the current lack of transgenic sugarcane options engineered for pest resistance to key Australian pests such as greyback canegrub (*Dermolepida albohirtum*) (Budeguer et al., 2021).

3.5 An uncertain future for integrated pest management in the GBR catchments

Integrated Pest Management (IPM) involves the careful science-based integration of multiple pest control techniques, combining biological, chemical, physical and crop specific (cultural) management strategies and practices to grow healthy crops, and minimise the use and risks of pesticides to human health and the environment (Deguine et al., 2021). IPM also relates to managing issues such as pesticide resistance development. Much like the global IPM experience, GBR pesticide policy must now grapple with a fragmented IPM landscape across increasingly diverse commodities, pest issues, and market forces. Few HS issues produced the divergence in responses as IPM, and its current and future prospects, from participation feedback across different industries.

3.5.1 IPM in sugarcane

HS ratings and feedback around major industries such as sugarcane suggested limited opportunities for IPM around the dominant pest management challenges of weed impacts (with already widespread green cane trash blanket practices noted as the most effective current option cf. other cultural controls such as planting density). Much future sugarcane IPM will continue to emphasise pest and disease resistance in plant breeding (i.e., varietal tolerance to various pathogens), with options for other non-pesticidal practices generally regarded as limited by most HS respondents. Interestingly, despite the often ambivalent commentary around the utility of IPM in sugrcane, respondents still noted diverse strategies in their feedback, such as control of localised fall army worm (*Spodoptera frugiperda*) outbreaks through protection of beneficial predators and economic thresholds; and utilization of emerging drone technologies to better identify and support informed decisions around control of pest outbreaks (i.e., detection of early greyback canegrub damage) through strategic ‘surveillance and area-wide management’ type approaches. Use of longer (and even multiple) fallows as a cultural control of always problematic grass weed seed banks; and the as yet unexplored potential of increased planting density as a cultural control to reduce weeds were also noted by respondents as applications of potential IPM-type approaches in the sugar industry.

The underappreciated value of sound agronomic practices and other elements of farming sustainability (optimising nutrient and water use efficiency, soil health) in increasing farm resilience to pest impacts was also repeatedly highlighted in responses around IPM. The role of soil carbon in increasing disease resistance and ‘binding’ pesticides was noted as a particular information gap. Broader farming system interventions such as intercropping (short duration cover crops grown in the interrow) were also noted as promising sustainability options (including for non-pesticidal weed control), but uptake remained significantly challenged by issues such as moisture and nutrient competition with the sugarcane crop, and operational complexity for farmers. Co-benefits from sunn hemp (*Crotalaria juncea* L.) cultivation, currently emerging as fallow or green manure crop in sugarcane, for non-chemical nematode (bio-fumigation) and weed control (Sarkar et al., 2015) were also noted as gaining recent traction, but yet to be comprehensively ground-truthed with research.

3.5.2 IPM in horticulture and bananas

The relevance of IPM concepts (broadened to Integrated Pest and Disease Management; IPDM in bananas) and its on-ground application appears to be undergoing a resurgence in commodities such as bananas and some other horticultural crops. Imminent, or existing changes to available pesticide chemistries has thrust alternative pest control approaches to forefront of industry pest control efforts and research. In-field practices (de-leafing, reducing diseases levels prior to fungicide applications to minimise resistance risks) and research into predatory-parastitic insects, fungal entomopathogens for bunch pests, and other bio-controls remain major industry priorities. The use of alternative management strategies to the use of non- synthetic chemical options such as neem oil, pyrethrins and biological insecticides (i.e., *Bacillus thuringiensis* subspecies), and the use of predatory wasps such as *Eretmocerus hayati*–for silver leaf whitefly control (*Bemisia tabaci*) is also more prevalent in horticulture industries, when compared to industries like sugarcane.

4 Discussion

Collectively, identified HS issues spanned essentially the entire regulatory, socio-economic, agronomic, broader sustainability product selection and on-ground application elements of pesticide management by GBRCA farmers and their agricultural service providers (Figure 1). Some emergent HS issues did align with, or received recognition, under SCS process outputs (i.e., pesticide resistance, variable IPM implementation; Davis et al., 2024), a not surprising outcome given initial issues were based on SCS literature review outputs. Notably however, several of the most critical, and highest ranking, identified issues likely facing pesticide water quality management in the GBRCA did not emerge clearly from SCS literature approaches, or received only cursory attention, despite potentially profound implications for farming and associated water quality management policy (i.e., rapid changes in pesticide application behaviours due to regulatory or product availability changes; the rise of private sector agronomic extension; farming advisor, agrochemical reseller-spray contractor policy gaps; lack of industry standards and baseline data on pesticide application equipment across industries). Future GBR pesticide policy needs to be aware of this entire gamut of looming macro- through to micro-scale issues to avoid ineffective, or possibly even perverse, policy implementation over the longer term.

4.1 Policy recommendations

Policy responses for pesticide management in the GBRCA will need to span a broad range of regulatory, research and extension agendas. The variable scale and diversity of industries and issues itself will, in itself, pose policy implementation challenges. In industries largely concentrated within the GBRCA (sugarcane, bananas), some policies can likely be effectively implemented at industry-wide, state-level or even regional scales. Others dealing with national-scale industries such as broad acre cropping and horticulture, or issues of pesticide regulatory processes, will likely need addressing at national scales. Some HS challenges identified

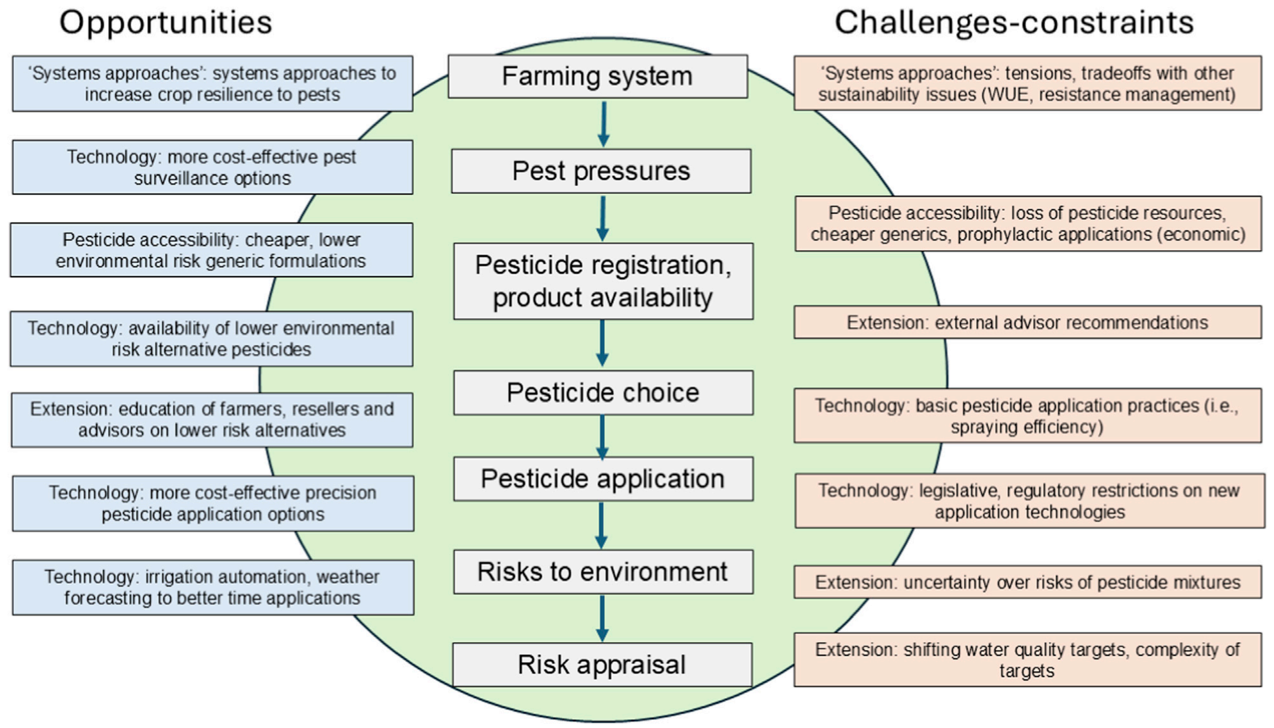

FIGURE 1
Summary of Horizon Scanning outcomes in thematic opportunities and constraints, and their relevance to pest management in a farming system hierarchy.

here (agrochemical reseller and private agronomy consultant engagement, support for early career extension professionals) are already being addressed at some, typically localised levels, but need broader and more consolidated roll-out. Similarly, several priority issues such as management of pesticide resistance, regulatory changes to key pesticides affecting entire industries, and pest-range shifts pose governance challenges at the regional, and even broader scales, requiring adaptive, inter-catchment cooperation. While detailed policy responses are beyond the scope of this HS exercise, overarching policy principles should emphasise development of much stronger transdisciplinary frameworks involving more industry consultation and co-design of research and communication-extension agendas.

4.1.1 Greater emphasis on transdisciplinary policy and research frameworks

HS outcomes clearly identify a growing need for a longer-term, wider framing of policy and research into GBRCA pest management challenges and solutions, within whole-of-farming system sustainability outcomes. Much of the Reef Plan 2050 policy environment, its underpinning Paddock to Reef monitoring and modelling framework (Carroll et al., 2012), and the SCS process itself, remains implicitly reductionist, focused almost exclusively on the scale of applied pesticide losses from paddocks in appraising benefits of different farming practices (losses of grams of active ingredient applied). HS outcomes highlight emerging trade-offs and areas of tension with a range of other agricultural and sustainability policy goals, also an increasingly recognised challenge in the global pesticide policy arena (Finger, 2018; Möhring et al., 2020; Brunelle et al., 2024). Precedents for more system-oriented modelling of collective environmental impacts of farming practice change scenarios (water quality but also other sustainability issues such as soil losses, carbon emissions, weed resistance, economics etc.) are available (see van der Werf et al., 2020; Van Deynze et al., 2022). Some very recent GBR studies integrating water quality (pesticides, sediment, nutrients) and economic outcomes of whole-of-farming system changes (Thompson et al., 2024) involve significant increases in the quantum of research complexity, but offer more holistic appraisals of cost-benefits of practice change, and better framing of management practices within a broader natural capital landscape for farming, and optimizing ecosystem services within agro-ecosystems.

The level of GBR policy engagement with key agricultural industries has been inconsistent through time, with initiatives such as 'Pesticide working group' collaborations emerging organically in the past, but struggling for longevity without leadership, support, clear directives, and stakeholder perceptions they are token 'industry consultation' with limited tangible influence on eventual policy. Reinvigorating these relationships to work with industry in quantifying potential changes in pesticide usage patterns in response to regulatory reviews (and modelling corresponding changes in off-farm water quality) would seem a priority first step in helping frame and 'future proof' policy directives. With issues such as global climate change recognised as the primary threat to long-term GBR health (Waterhouse et al., 2024) and also emerging in other global catchment-watershed horizon scanning exercises (Pérez-Jvostov et al., 2020; Herbert-Read et al., 2022; Jones et al., 2025), GBR policy must be cognizant of more than just water quality outcomes in appraising farming practices.

A wider, transdisciplinary framing of pest management, involving multiple actors and public–private collaborations that enable co-development of pest control technology (including both organic and synthetic chemical options), systems, and socio-economic approaches to better understand farmer decision-making are also increasingly advocated (Goebel and Nikpay, 2017; Neve et al., 2018). Notably, the identification of 'siloed, niche specialisation' and recognition of the limitations of overtly 'pest-centric' management (including IPM), has led to growing advocacy for even broader "crop-oriented" paradigms that emphasise systemic, agro-ecological approaches (Deguine et al., 2021; Altieri et al., 2024). IPM approaches seem well-entrenched, more systematically applied, and continuing to mature in GBRCA commodities such as bananas and horticulture. Bearing in mind the increasingly congested conceptual space of sustainable agriculture, this may be an opportune time for paradigm shifts toward embedding GBR pest policy within more 'cropping system-oriented' frameworks. This re-alignment could help guide future policy and research in key commodities such as sugarcane, for example, which lack systematic clarity in the IPM arena, and currently face a range of emerging tensions and trade-offs across different elements of holistic farming sustainability. These new frameworks should emphasise soil health, biological and agronomic components of entire cropping ecosystems, invest into new R&D of non-synthetic control measures to address pest issues, as well as the social and institutional interactions across the different stakeholders involved in crop protection (farmers, researchers, decision-makers, policymakers, advisors, buyers, consumers, processors, agrochemical suppliers, etc. Deguine et al., 2021; Brunelle et al., 2024). Recent novel approaches to utilising market incentives (subsidies, insurance etc.) for adoption of lower risk nutrient management practices in GBR cropping systems (Thorburn et al., 2020; 2024) could also hold promise for extension into low-risk pesticide management practice improvements and IPM adoption.

4.1.2 Fit for purpose extension

GBR Pesticide policy needs to better engage with an increasingly diverse and pluralistic farmer advisory system, due to its broadening commodity scope, but also the parallel transformation seen globally (i.e., withdrawal of State involvement and an increased role for private, commercial service providers). Many of the identified HS constraints in the extension-engagement space are far from unique. The need for training of agrochemical resellers, agronomists, farmers and delivery providers to secure the basics of sprayer calibration and adjustment to facilitate both current best practice, but also future assimilation of new technological advances in precision agriculture are well-recognised in other countries (Gil et al., 2024). Similarly, the training of advisors or chemical distributors are becoming increasingly mandatory in many countries, in order to ensure that up-to-date technical information and sustainability approaches are disseminated through agricultural decision-making ecosystems (Lefebvre et al., 2015). The need for GBRCA agrochemical reseller training around pesticide sustainability, by experienced staff with industry credibility, was a consistent theme of HS responses.

'One size fits all' extension (and policy) models are also clearly going to struggle for traction across the diversity of farming systems and the high- and low-profit margin per hectare commodities increasingly captured under the newer end-of-catchment 99% ecosystem protection targets. Approaches such as social network analysis and clear definition of industry advisor typologies (see Paschen et al., 2017) are needed to better understand the opportunities and gaps for government/public, industry and private sector actors to collaborate in pesticide BMP extension service delivery across different commodities in the GBRCA. Global experiences highlight the use of pesticides and prevention measures by farmers differ systematically depending on who advises them, particularly with respect to public versus private advisors, and extension services affiliated with companies selling pesticides (Wuepper et al., 2021). In an increasingly complex BMP and regulatory environment for farmers, environmental awareness and extension networks will be foundational in ensuring progress toward sustainable farming, particularly considering the increasingly contested science-policy landscape identified in HS feedback.

4.2 Conclusion

The use of horizon scanning in conservation and natural resource management is an increasingly important component of policy 'best practice'. The decision-making environment surrounding agricultural pesticide usage in the GBR catchment area is pesticide clearly impacted by a range of rapidly evolving and shifting regulatory, technological and advisory contexts. Consensus exercises, like the SCS, based largely on systematic peer review of published scientific literature, will likely always struggle to capture issues at the forefront of agricultural sustainability, particularly considering lag times for scientific peer review and publication, and cyclical, 4–5-year time frames in reviewing published science to inform policy. This Horizon Scanning exercise is not intended to divert policy attention from contemporary research and existing SCS-identified practices known with high certainty to provide substantial environmental benefits. Instead, it aims to provide an additional modification to SCS processes, supplementing a more academic exercise with on-ground, industry relevant forecasting and input. If the GBR pesticide policy environment is to avoid the pitfalls and limitations of overtly pest-centric policy and management perspectives seen globally, more forward-thinking, integrated and adaptive policy and forecasting frameworks will undoubtedly be required.

Many of the identified issues can be addressed with strategic planning, long-term investments in research and monitoring, extension, and implementation of adaptive management frameworks to complement SCS implementation and associated policy decision making. Unless certain fundamentals are addressed (baseline data on practitioners and practices, spray equipment standard compliance, reseller-advisor sustainability training etc.), many of the same behaviours will continue and generate limited measurable improvement, regardless of other policy improvements. While the water quality risk appraisal framework for GBR pesticides is becoming increasingly integrated, HS outcomes highlight the need to stimulate considerably more integrated, multidisciplinary research investment and policy responses to manage these risks.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided written informed consent to participate in this study.

Author contributions

AD: Conceptualization, Writing – original draft, Investigation, Writing – review and editing, Methodology, Formal Analysis, Data curation. SA: Methodology, Writing – review and editing, Investigation, Conceptualization, Writing – original draft. LD: Writing – review and editing, Methodology, Writing – original draft, Conceptualization, Investigation. ES: Methodology, Conceptualization, Writing – review and editing, Investigation, Writing – original draft. RS: Methodology, Writing – original draft, Conceptualization, Investigation, Writing – review and editing. RM: Methodology, Conceptualization, Investigation, Writing – review and editing, Writing – original draft. EF: Methodology, Writing – review and editing, Investigation, Writing – original draft.

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Conflict of interest

Author SA was employed by Agritech Solutions. Author ES was employed by Farmacist, Ayr, QLD, Australia. Author RS was employed by Farmacist, Sandiford, QLD, Australia. Author EF was employed by Sugar Research Australia, Meringa Office.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1683340/full#supplementary-material

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