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Integrated Management of Northern Australian Grains to Ensure Market Access

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Acronyms

GRDC: Grain Research Development Corporations

DPI: Department of Primary Industries

Project Participants

Project Participants:

[1]P Brodie Holdings Property Limited, PB Agrifood Australia Limited, Townsville, Queensland, 4350, Australia

[2]TriCal Australia Property Limited, Edinburgh, South Australia, 5111, Australia

[3]Douglas Products, and Packaging Company, Liberty, Missouri, 64068, USA

[4]Archer Daniels Midland Company Property Limited, ADM, Chicago, Illinois, 60601, USA

[5]Grain Research Development Corporations (GRDC), Barton, Canberra, 2600, Australia

Executive Summary

Following harvest, grains must be stored safely for prolonged periods to ensure market access throughout the year. As broad acre cropping expands in northern Australia, on-farm storage is gaining momentum with a special emphasis on promoting the regional grain value chains to service domestic and international markets. However, the warm and humid climate of northern Australia is conducive to pest attacks and moisture build-up threatening the safe storage of grains. The lack of expertise and research data on grain storage further escalates this risk and constitutes an impediment to long-term investment in this area, suggesting the need for comprehensive research addressing this issue.

Considering this, an industry-driven research project, "Integrated management to ensure market access for northern Australian grain" has been initiated by CRCNA, which aims to establish effective pest and resistance management practices that are suitable for the northern tropics. The objective of this project is threefold: establishing pest and resistance profiles [1], identifying effective chemical and non-chemical control strategies that can potentially be used in farms and other stake holdings [2], and outreaching key findings of the project to the industry for adoption [3]. Approximately 280-grain samples were collected representing selective growing regions in QLD, NT, and WA covering the entire northern tropic belt. The collected commodities were cereals (sorghum, maize, and wheat) and pulses (soybeans and mung beans). Sample screening clearly indicated that the red flour beetle, *Tribolium castaneum* is the dominant pest species in the northern region and strongly phosphine-resistant populations of this species exist in very high frequency, irrespective of some differences in commodities stored between the three state jurisdictions. Overall, the pest species and resistance profile confirmed the existence of some region-specific variations, suggesting the need for establishing and implementing region-specific management practices. Mass trapping of key grain insect pests across the Burdekin region identified that pest peaking and lean seasons in the region were wet summer and winter. The former coincides with the primary harvesting season, thus, prior cleaning of the storage structures with structural treatment and implementing other hygiene practices during the lean season would greatly help in reducing the infestation and spread in the region. While gas-tight phosphine fumigation over 7 days is very effective against many of the phosphine resistant insect pests, the break fumigant, sulfuryl fluoride, is essential to alleviate strongly resistant rusty grain beetle, *Cryptoelstes ferrugineus*. The triplet grain protectant combo, spinosad, s-methoprene and chlorpyriphos is effective in controlling all the major stored product pests, long-term residual efficacy needs to be evaluated. Though the structural treatment with Diatamaceous Earth (DE) was effective against the lesser grain borer, *R. dominica*, and rice weevil, *Sitophilus oryzae,* its efficacy against red flour beetle and rusty grain beetle is relatively low, thus, care needs to be undertaken while applying DE on concrete or steel. Several project workshop meetings have been carried out in Townsville in collaboration with other stakeholders with a focus on maximising the rate of adoption of scientific changes in practice. The project team also developed region-specific IPRM and delivered it to the industry for wider adoption. Key findings were also presented at three (2 national and 1 international) conferences and published to escalate the impact of this overall research in northern Australia. Overall, the project ensures knowledge-based transitioning in this region, particularly when grain storage is still in its infancy. This will help achieve storage integrity and maximize the efficiency of the grain value chain in this region, ensuring that farmers can be "price makers' and not "price takers."

Key project outputs delivered:

- For the first time, regional species composition for the insect pests that infest stored grains and processed products has been revealed for each of the grain growing regions in northern QLD, NT and northern WA and shared with the key industry stakeholders. This has increased the knowledge and awareness of the timely detection and management of these insect threats with the functioning grain supply chains in Northern Australia.
- Baseline susceptibility levels of multiple grain insect populations to different chemical treatments (fumigants, phosphine, sulfuryl fluoride and contact insecticides) were characterised. This led to the establishment of suitable industry-specific pest and resistance intervention strategies for the region.

- These pest intervention strategies were validated in the field in collaboration with growers and key industry stakeholders, emphasizing the adoption of scientific management practices in grain storage in Northern Australia.
- Multiple field day/ demonstration workshops (online and in-person) have been executed across the northern region in collaboration with key QDPI extension staff and private sector agronomists, promoting awareness of the problems in grain storage and pest management and controlling them on time.
- An integrated pest and resistance management program (IPRM) – a strategy document has been drafted along with multiple grower interviews and submitted for publications in GRDC Ground Cover and the Australian Grain, escalating the project impact and wider adoption among the industry.

Expenditure Summary

The total expenses incurred over the proposed three-year period was AU$ 449,884. This is mainly operational and includes staff salary, laboratory consumables, bench fees, and domestic travel. Regarding in-kind, the lead organization, QDAF had contributed AU$ 36, 643 whereas, the corresponding contributions from all the project participants were as follows: AU$ 3,125 (Archer Daniels Midland Company Property Limited, ADM), AU$ 3750 (Douglas Products, and Packaging Company), AU$ 1875 (Grain Research Development Corporation, GRDC), AU$ 2500 (P Brodie Holdings Property Limited) AU$ 3125 (TriCal Australia Property Limited). Thus, the total in-kind contribution for the project is $AU 51,018 (QDAF, $AU 36,643 plus all industry participants, AU$ 14,375) for this quarter.

Introduction

Northern Australia, the area north of the Tropic of Capricorn, traditionally has been a hub for pastoralists and cane growers, though, is now becoming the future agricultural development frontier. Broadacre cropping expanded substantially in this region, and the watershed moment arrived when sugarcane or cotton cropping was rotated with fallow grains or pulses, maximizing net farm profitability. Long-term rotational cropping of grains (sorghum, maize, and barley) or pulses (mung bean, chickpea, and soybean) with sugarcane has increased net farm profits up to $2000/ha/annum in northern Queensland. Similarly, growing fodder crops in cotton belts of the Northern Territory has augmented the local livestock industries, promoting crop diversity. Therefore, venturing into broadacre cropping in northern Australia not only reduces the financial risks due to monocropping but also minimises the overall environmental footprint (e.g. reduction in fertiliser inputs). Research trials on other valuable crops, such as peanuts, industrial hemp, and sesame are also currently in progress in selected places, with the perspective to promote regional business and the long-term sustainability of the agricultural sector in the far north.

While agriculture in northern Australia is transitioning, on-farm storage of harvested grains is gaining momentum with a special focus on servicing both domestic and international markets. The benefit of storing grains after harvest is twofold: 1. it provides growers greater flexibility in understanding the market landscapes and 2. facilitates growers to consolidate a larger grain load and claim freight discounts. However, region-specific information on the scientific storage and management of high-quality grains is lacking. For instance, foundational information such as establishing the right structure is paramount for this region. Furthermore, the warm and humid climate of the north could pose serious risks to storing grain safely from insect pests and microbial pathogens. The proximity of the northern Australian coastal belts to other Asia-Pacific trading partners also holds some levels of risk for new insect incursions, affecting overall national grain biosecurity and sustainability. Therefore, scientifically sound storage and pest management practices that are suitable for the northern region are needed.

The current project explored several scientific components in grain storage for the northern tropics and generated region-specific information on understanding the bio-ecology and the management of key grain insect pests. The key findings of this project are discussed below.

Grain sampling and survey: In total, 80 grain storage sites were surveyed across northern Australia over two years (2021-2023), covering multiple wet summer and dry winter seasons. This includes 57, 12 and 11 storage sites in Queensland-QLD (Townsville, Mackay and Atherton Tablelands), Northern Territory-NT (Douglas Daly, and Tortilla Flat) and Western Australia-WA (Broome and Kununurra) (Figure 1). Two hundred and eighty-grain (280) samples were collected and screened in the laboratory, which yielded around 472 live grain insect pest populations (Table 1-5). On average, 66% of the grain samples were infested with at least one of the major grain insect pests confirming that the infestation level and pest pressure are high. Overall, the results indicate that most likely every farm in northern Australia could harbour five or more grain insect populations.

Pest infestation profile: Three insect species that spend most of their life cycle outside the grain (external feeders) were found consistently across the northern region, covering all three states (QLD, NT and WA). These include the Red Flour Beetle (RFB), *Tribolium castaneum* (Herbst), the Saw-toothed Grain Beetle (SGB), *Oryzaephilus surinamensis* (Linneaus), Rusty Grain Beetle (RGB), *Cryptolestes ferrugineus* (Stephens). Among them, RFB remained the most prevalent pest species in the entire north (**Figure 2A-C)**. Two other major internally feeding insect species Lesser Grain Borer (LGB), *Rhyzopertha dominica* (Fabricius.) and Rice Weevil (RW), *Sitophilius oryzae* (Linnaeus) were also identified, though infestation of these species was confined to some of the selected states. For instance, RW infestations were not found in northern WA. Commodity-specific insect pests such as the Maize Weevil (MW), *Sitophilus zeamais* (Motschulsky), the Cowpea Bruchids (BDS), *Callosobruchus maculatus* (Fabricius) were found in small proportions in selected sites of QLD and NT **(Figure 2A-C)**.

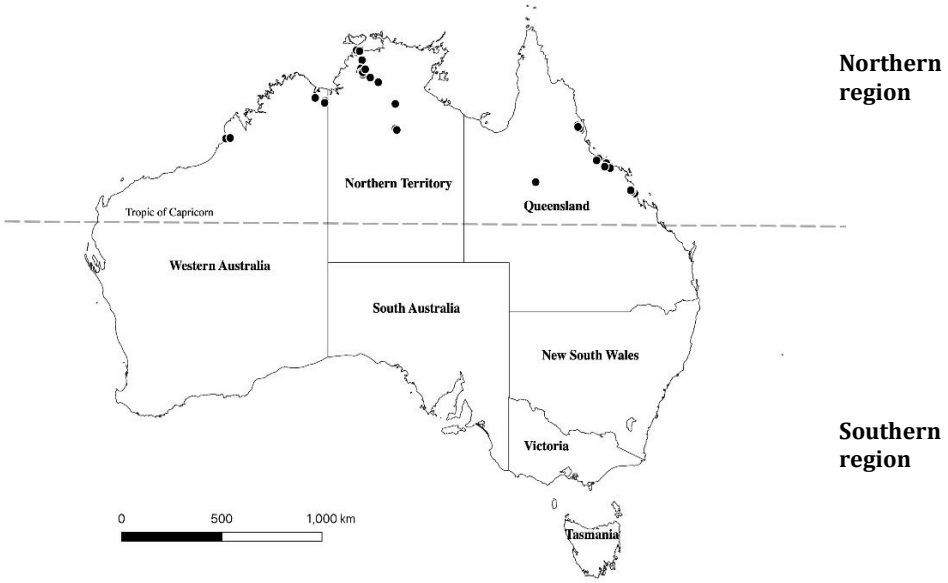


Figure 1. Map of Australia showing sample collection sites in northern region.

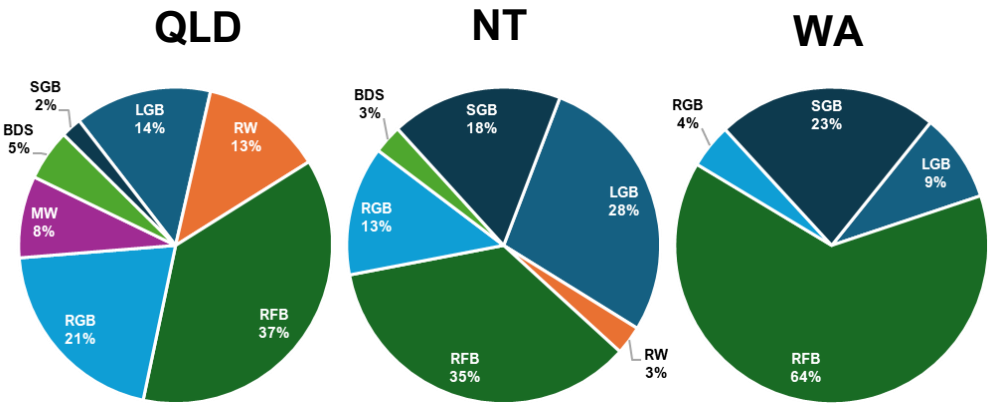


Figure 2. Insect infestation profile in grain samples collected from northern Queensland (A), Northern Territory (B) and Western Australia (C).

Overall comparison of insect composition profile in grain samples across the northern region (QLD, NT and WA) reaffirms the dominance of RFB (35-64%) followed by LGB (9-28%), RGB (4-21%), SGB (2-23%) and RW (3-13%). While similar insect species composition is observed in the southern region, the proportion of insect infestation registered in this region was relatively low (Figure 3). For example, a comparison of pest infestation data recorded at the storage site level indicates that the range of RFB infestation reported for the southern region was 23-54.5% for the years, 2021-2023, whereas it was 63.3-83.3% for the north (Figure 3). Such a difference could be due to the warm and humid conditions of the tropics favouring the higher breeding and movement of these insect pests, especially in externally feeding insects.

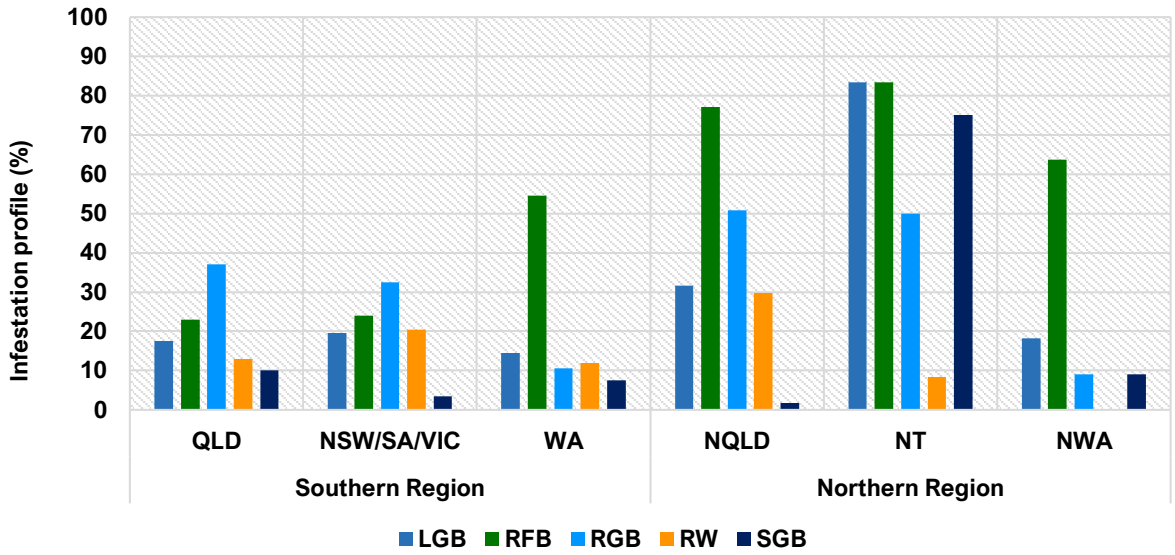


Figure 3: Comparison of insect infestation profile between the grain growing regions in southern and northern Australia over the period 2021-2023.

Efficacy of fumigants, protectants, and resistance profiling: Susceptibility to phosphine (PH_3): All field-collected insect populations were subjected to PH_3 susceptibility tests [1]. escalating the overall resistance percentage of this region to 41% (Tables 6-10). The RFB and RGB registered a maximum of 100 and 99% strong resistance, respectively. This is higher than the average resistance percentage values reported for the south (QLD, NSW, VIC, SA, and WA) over the last three years (13-32%, data obtained from the national resistance monitoring project, DAQ2209-001RTX). Yearly dissection of resistance data in selected study regions indicates that strongly resistant RFB populations exist in higher proportions in the north in comparison to the south. For instance, in the year 2022-2023, the range of resistance percentage observed in RFB populations in the northern region was 50- 91%, whereas it was 8.5-35% for the southern region (Figures 4 and 5). The current study stands first in reporting strongly resistant RFB in northern WA and NT with the resistance frequency ranging from 4-95% and 1-9%, respectively. The detection of strongly resistant RFB in the north, particularly in WA at higher proportions, blows the whistle, as resistant insects in WA are considered biosecurity incursive threats. The second most challenging pest species that deserves attention in this region is strongly resistant RGB. Though resistant populations were confined to northern QLD alone, nearly half of the populations collected were strongly resistant to phosphine (Figure 4) and failure to control these populations on time could favour the rapid spread of these populations to other regions. This could seriously affect the functioning of the regional value chain and impede trade.

While grain storage is relatively new for the northern region, the observed higher resistance percentage in RGB (53.5%) and RFB (50.7-91.6%) is concerning and demands the urgent need for developing and deploying region-specific pest and resistance management strategies (Figure 4). Moreover, awareness of scientific storage of grains and controlling resistant insect pests is lacking thus extension education on these topics is pivotal for achieving broader impacts.

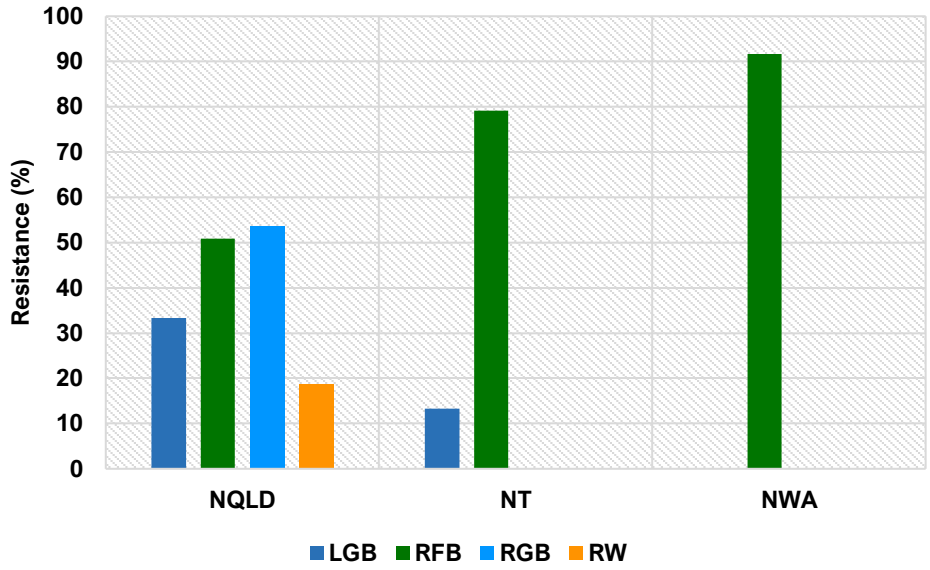


Figure 4: Per cent strong resistance to fumigant, phosphine (PH_3) in four major grain insect pets collected from northern Australia in 2022-23

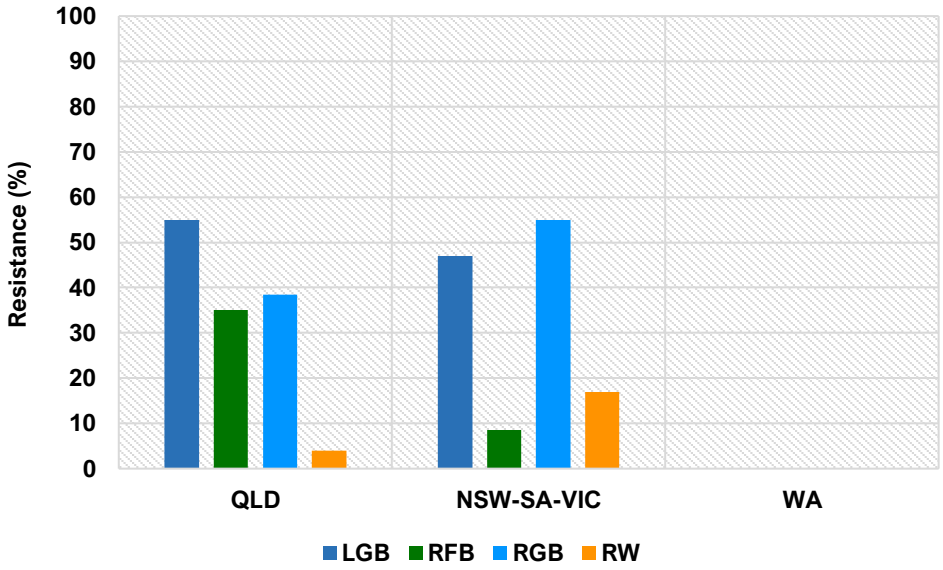


Figure 5: Per cent strong resistance to fumigant, phosphine (PH_3) in four major grain insect pets collected from southern Australia in 2022-23

Laboratory susceptibility studies ($LC_{50/99.9}$) to PH_3 performed at 25 and 30°C against three insect species, RW, MW, and BDS (Tables 11 and 12) indicate that a low dose rate of PH_3 (56 g hm^{-3}) can effectively be used to control these insects in the northern tropics.

Susceptibility to sulfuryl fluoride (SF): None of the RFB populations collected from northern Australia survived the SF discriminatory dose of 1.72 g hm^{-3} over 48 hours, confirming the lack of resistance to SF in the region [2]. Laboratory SF fumigations at 30°C and dose mortality response analysis ($LC_{50/99.9}$) confirmed that one-third of the current label rate (500 g hm^{-3}) over a 4 to 7-day exposure period was effective in controlling three major regional insect pests, RW, MW, and BDS (Table 13, 14 and 15).

Susceptibility to grain protectant and structural treatment: Populations of LGB, RFB, RGB, RW, SGB, and MW were challenged with triplet combo, spinosad + chlorpyriphos-methyl + s-methoprene (SCS) -treated grains [3] and diatomaceous earth (DE)-sprayed concrete and steel surfaces [4]. The SCS-treated wheat caused complete control of all the 21 insect populations tested at 35°C, suggesting that it can be used as one of the important tools of IPM for the region (Table 16). Results of surface treatment with DE revealed tolerant survivors in six of the nine RFB populations tested, and the observed mortality range among these populations was 59.8-98.4% (Tables 17 and 18). Though steel surface treatment was relatively more effective, substantial individuals in two of the RFB populations survived the treatment, suggesting DE may not be effective in the region (Table 19). The highly humid environment perhaps interferes with the efficacy of the compound.

Insect trapping and monitoring: Results of trapping [5] in the Burdekin grain supply chain over 17 months (Oct 2022- Feb 2024) confirmed that LGBs and RFBs were the most common pest species of this region (Table 20 and Figures 3). The maximal populations of LGB and RFB were trapped during April-June, which is typically a transition period from wet summer to dry winter for the region (Figure 6). In contrast to the above, the traps captured a maximal number of RW in the dry winter season, after June (Figure 2). Preliminary analysis of insects trapped at various grain storage nodes indicated that pest pressure is lower at the port and the paddock than at farms and feed mills. Feed mills had a single peak of insect numbers trapped from June-October, whereas farms, had two seasonal trapping peaks (March-June and July-October), (Figure 6) suggesting the importance of establishing node-specific pest intervention strategies.

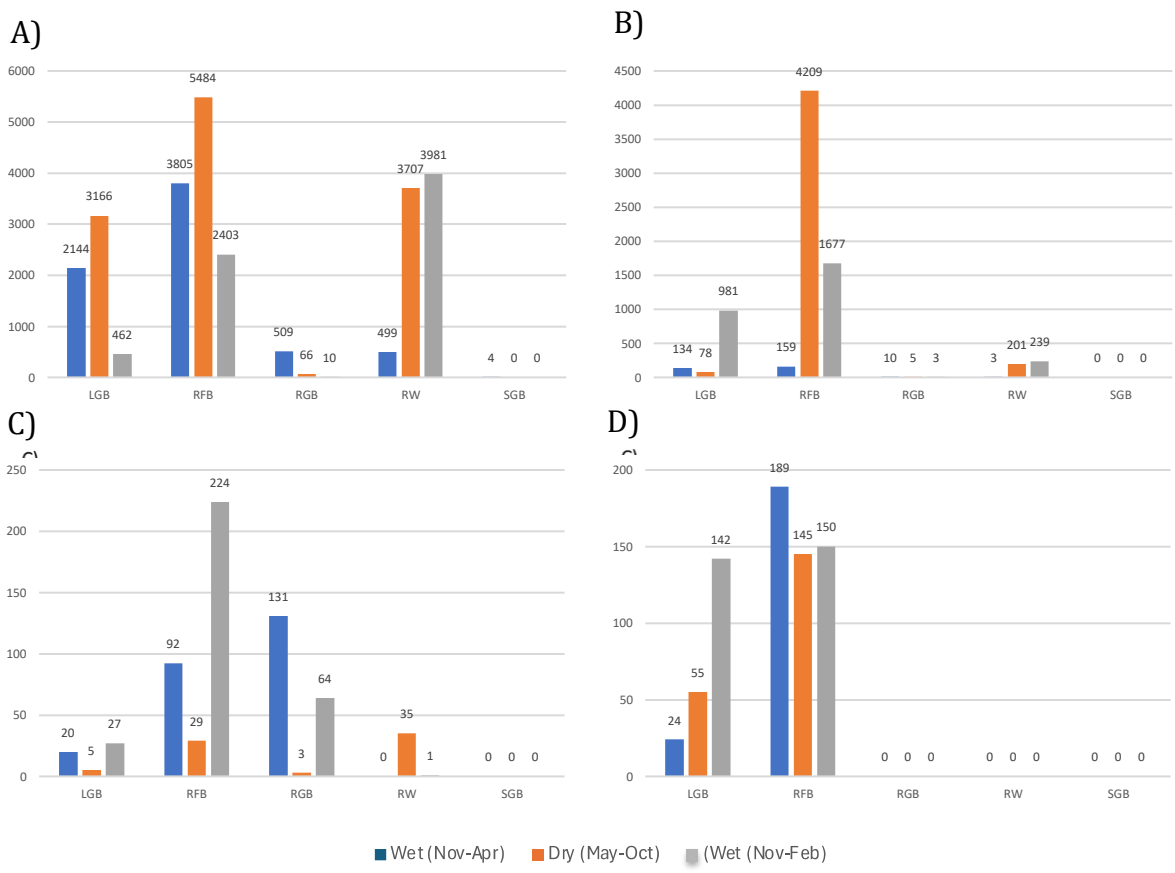


Figure 6. Variations in insect numbers trapped across the grain value chain over 17 months. The sampled storage sites include storages located in farms (A), feed mills (B), port (C), and paddocks/grassland (D). The number presented includes insects captured from all three trap types (Dome, Baited Lindgren, and Unbaited Lindgren trap).

The cumulative insect numbers trapped over a year Nov-2021 to Oct-2022 in multiple storage sites (farms, feed mills, bulk grain companies) of this region were above four thousand for three of the major species, RFB, LGB and RW investigated. Pest numbers peaked in both seasons, the wet summer (Nov-April) and the dry winter (May-Oct) **(Figure 7).** For instance, RFB and LGB were trapped slightly higher in the dry season whereas it was the other way around for RW and RGB. The observed high pest numbers in wet summer coincide with major grain harvesting periods in the region and warrant the timely implementation of preventive insect control measures, possibly well before the harvesting commences. These include adopting site storage hygiene, treating storage surfaces with structural treatments (contact insecticides) and applying protectants on freshly harvested grains (if it is required). Such timely actions significantly reduce the overall pest pressure in the environment and anchor chemical control programs.

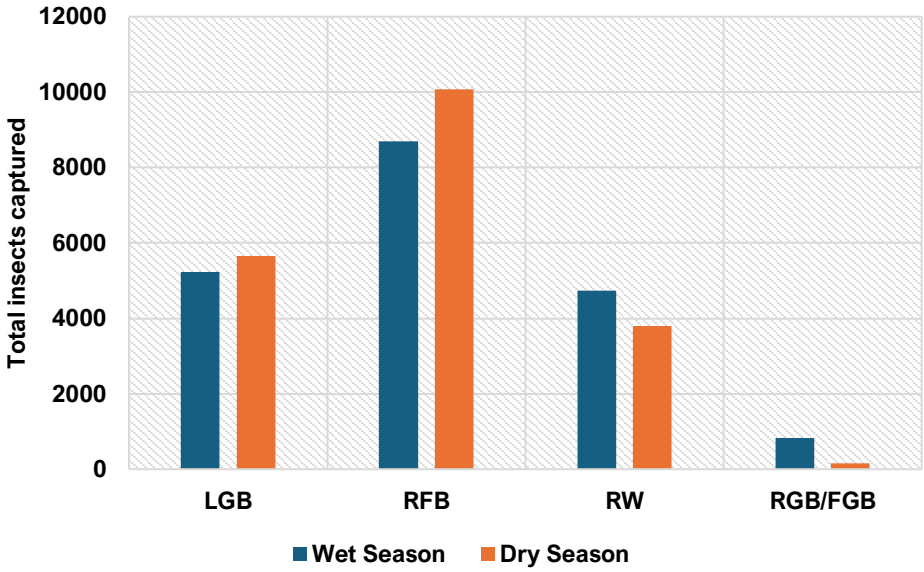


Figure 7: The total number of stored grain insect pests, Red Flour Beetle (RFB), Lesser Grain Borer (LGB), Rice Weevil (RW) and Rusty Grain Beetle (RGB) trapped in northern Queensland over 14 months.

Field validation trials: Two field research trials have been executed in collaboration with the industry with the perspective to validate laboratory findings and promote the adoption of scientific practices within the industry. The first trial involved fumigating a 168 m^3 steel silo located at Home Hill, Ayre, containing sorghum grains with aluminium phosphide tablets, following the label rates (1.0 g/ m^3 over 7 days). Live test insects of PH_3-resistant strains of multiple species were placed inside the silo before the fumigation. The PH_3 concentrations remained well above the target throughout the 7-day exposure period (Figure 8 A), confirming that the silo was gas-tight, and recirculation of fume was efficient. This fumigation caused complete mortality of all the insect life stages, including eggs of three strongly PH_3-resistant strains, RFB, MW and BDS. However, resistant strains of RGB (20-40%) and BDS (<1%) survived this fumigation, confirming that the 7-day exposure period is not adequate for controlling infestations of RGB and BDS (Table 21). In the second trial, the efficacy of one-third of the maximal registered CT of sulfuryl fluoride (SF) (1500 g hm^{-3}) was evaluated against PH_3-resistant strains of RFB, RGB, MW and BDS. The trial was conducted at the Size and Cogill's grain-handling facility at Townsville. A 344 m^3 steel silo filled with sorghum grains was fumigated with 500 g hm^{-3} of SF over 5 days and the recorded SF concentrations within the silo were within the target range (Figure 9A). Unlike PH_3, SF fumigation exhibited complete control of both the adults and progeny of all four target insect species (Table 22). The ambient temperature and relative humidity recorded for both trials were in the range of 20-30°C and 65-70%, respectively (Figure 8 B, C and 9 B, C).

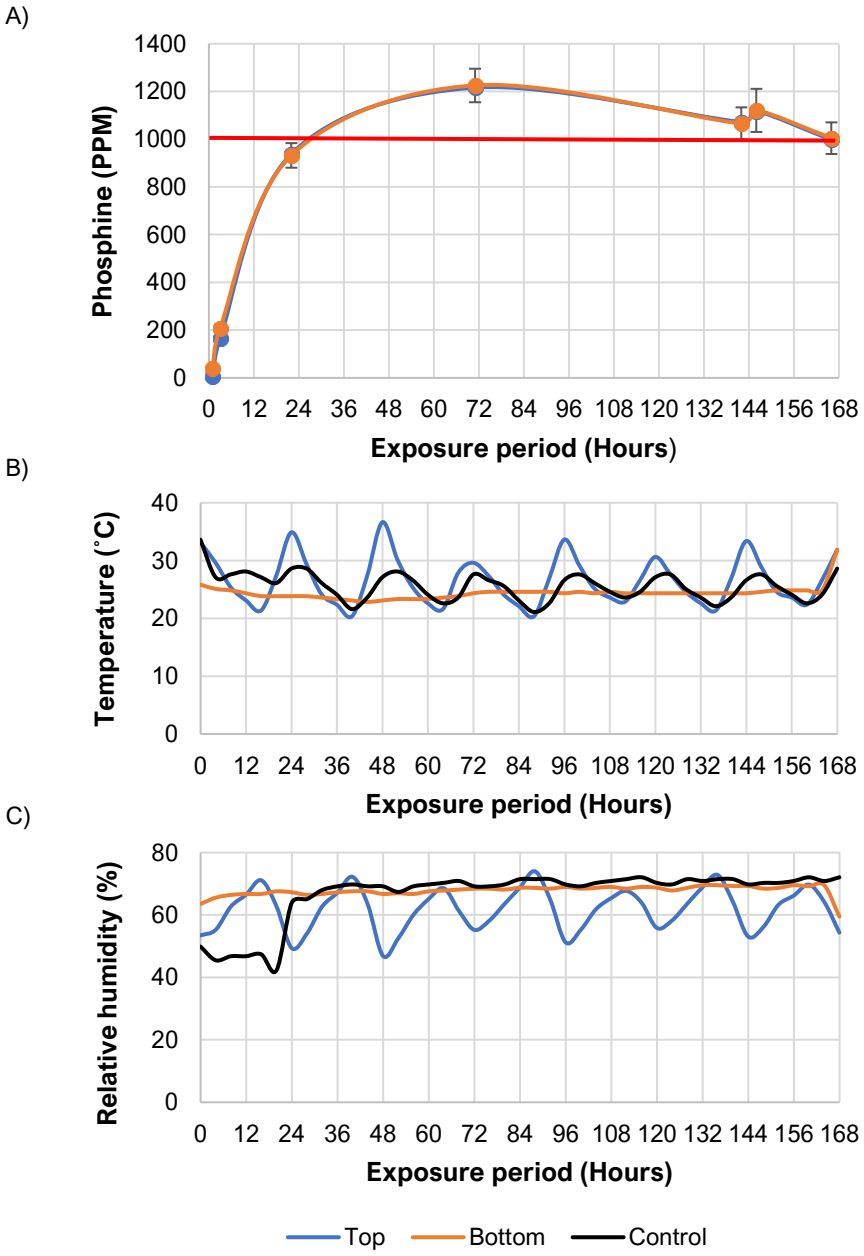


Figure 8. The recorded concentrations of the fumigant, phosphine within the 168 m^3 silo with sorghum grains over the fume period of 7 days (A). The recorded temperatures (B) and humidity profiles (C) for the ambient (from control grain bins), within the grains and headspace of the silo were shown.

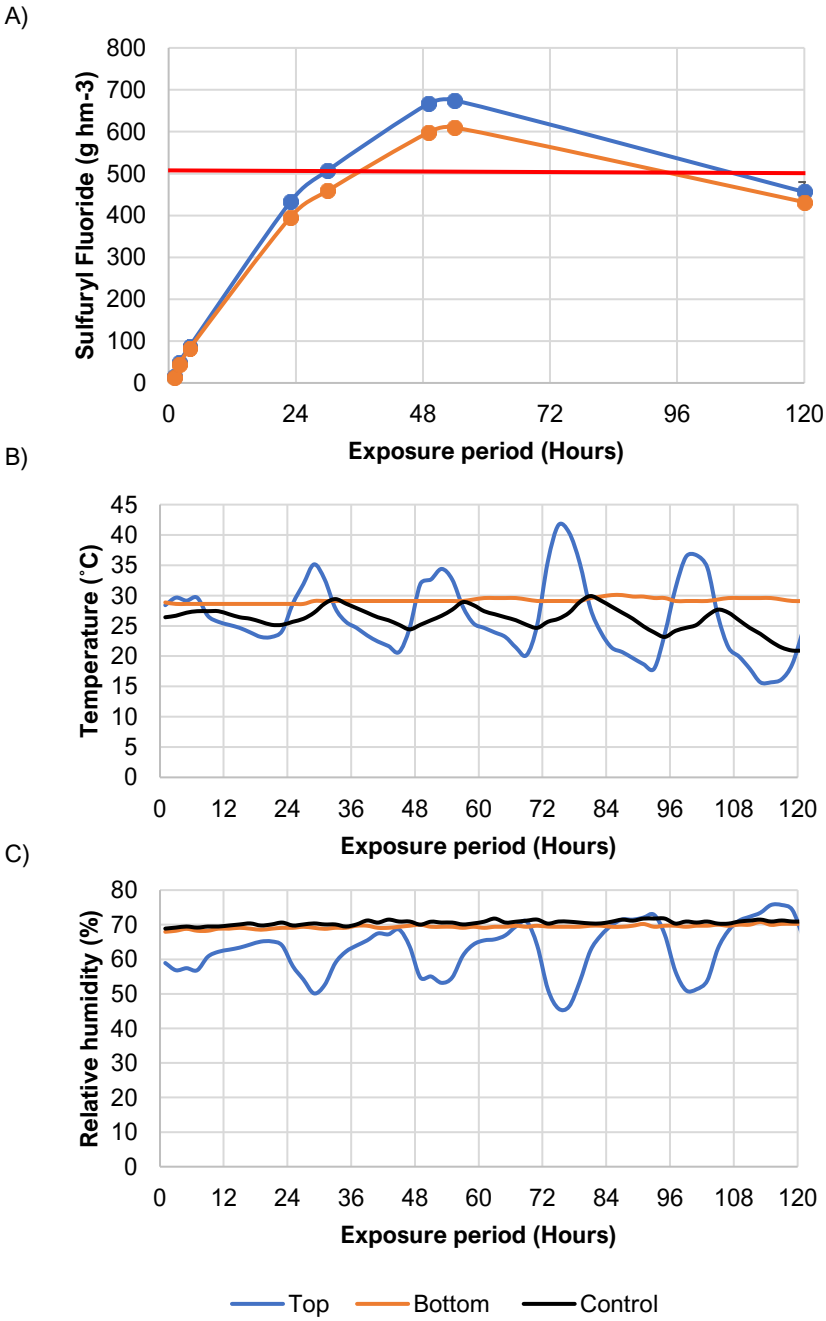


Figure 9. The concentrations of the fumigant, sulfuryl fluoride within the 344 m^3 silo with sorghum grains over the fume period of 5 days (A). The recorded temperatures (B) and humidity profiles (C) for the ambient (from control grain bins), within the grains and headspace of the silo were shown.

Project Extension and Communication: Three major communication events have been organised and key impacts were delivered in each.

Grain Storage Workshop Webinar for the North organised by the Extension team: The project leader (Dr Raj) attended this virtual event over three days (7^{th}-9^{th} August 2024) and interacted with researchers, agronomists and stakeholders from all three northern regions, Queensland, Territory and Western Australia.

Key issues such as pest species composition, differences in resistance levels and frequency and adopting key management strategies were discussed for each region.

International conference on controlled atmosphere and fumigation (CAF) of stored products in Winnipeg, Canada, and a post-conference visit to the USA: The project leader (Dr Raj) attended the 12th CAF in Winnipeg, Canada, between the 18th to 24th of August 2024 and presented key findings of the CRCNA in one of the major sessions: Resistance to fumigants. The topic of the presentation was "Combating pest and resistance in the tropics: implications for the grain industry" and thus created significant impacts on the other attendees, particularly in the Asia-Pacific region (India, Vietnam, Thailand, and Indonesia). Dr Raj utilized this opportunity and established a strong linkage with these countries and currently exploring possible international collaborations with the help of the CRCNA. Dr Raj also visited the Grain storage research laboratory at the University of Manitoba (UM), Winnipeg, Canada, the Entomology Division at the Kansas State University (KSU), Manhattan, USA, and the United States Department of Agriculture - Agriculture Research Service (USDA-ARS), Manhattan, USA, and initiated research linkages with each of these research institutes (refer to the supporting information attached). He also delivered a special invited entomology seminar at the KSU and interacted with peer researchers and graduate students. These interactions were mainly on promoting regional collaboration between the USA and Australia on postharvest pest and resistance management, targeting to achieve food security and improve market access with the sustainability perspective (refer to the attached supporting materials: presentation files, images, and video links for more information).

Final Project Workshop on the delivery and adoption: This workshop was held at the Central Queensland University (CQU) campus in Townsville City on the 2nd of October 2024. Lead growers, industry stakeholders and chemical company representatives attended this half-day event online and in person. The project leader, and other key presenters, Dr Ian Biggs (CRCNA program manager), Dr Leigh Nelson (GRDC), Mr. Brock Dembowski (QDAF) and Mr Chris Warwick (Primary Business) delivered key messages of the project and emphasized the importance of adopting the scientific findings of the current project. The panel members of this event also discussed the possibilities of extending the current research and extension work in new frames through the support of the GRDC/CRCNA linkage program in the future. Participants from various stakeholders such as PB-Agrifood, Sizer and Cogill, TriCal Australia, Douglas Products, CQU, Nutrient Ag, and GRDC also attended this event and provided positive feedback. The second half of the workshop involved two demonstration/interaction activities including, insect diagnostics and a visit to the grain storage facility at the Townsville port (refer to supporting materials for more information).

Interview statements from stakeholders

"*We deal with bulk grain every day in sheds and as a major exporting company, we use fumigant, sulfuryl fluoride primarily and adhere to "Zero live insect tolerance policy". The grain storage project for northern Australia is great and created awareness of little but important things such as knowing the bugs, their lifecycle and. resistance status, and how to prevent them. Our experience in trapping pointed out what to watch out for at different times, where the insects are breeding, and when they're most active. We wouldn't know any of these details so greatly appreciate the team that came out and executed this over the last three years."*

- **Hugh PATON, Sizer and Coggill, Townsville port, Northern Queensland**

"We mainly store grains from November through to May in a year, so were keen on knowing about when the insect numbers reach high or the other way. I always assume that February and March were probably the peak times for the grain insects to multiply in large numbers, but the sampling and trapping results showed that the maximum insects were trapped between April-June, which is interesting. Also, I learned that it is not just about controlling one insect, it is mostly about managing multiple types with different levels of resistance. I would like the monitoring research to continue and keep providing information on whether phosphine is killing these bugs."

- **Myles SGROI, Ayr, Northern Queensland**

"We've sort of started storing grains mostly for mung beans as it was our break crop and grown in rotation to sugar cane. Since our storages are not sealable, we rely heavily on aeration cooling for managing insect pests.

The learning is that even with full aeration in Burdekin, the grain temperature was sitting at 30°C perhaps because of high humidity which you wouldn't see anywhere else in Australia for prolonged periods. So, the information that the project generated on fan airflow rate (Litres per tonne) for the local conditions, using an automated control system is highly valuable. Similarly, it's great to see information revealing what are the local insects, their life cycles and resistance levels. I also recommend publishing some of these findings online (e.g. in YouTube videos) because growers don't always get time to go to field days."

-Paul Villis, Northern Queensland

Validation of key Integrated Pest and Resistance Management (IPRM) strategies: The project team also established reference insect populations for each representative growing region in northern Australia and validated the effectiveness of selected treatments. A region-specific IPRM strategy was synthesized and published in two major magazine articles, Ground Cover and Australian Grain for wider adoption and escalating the project impacts. The project leader has made substantial efforts in this regard already in collaboration with the CRCNA and GRDC.

Conclusions and Key Recommendations

The project generated first-hand baseline information on pest and resistance profiles for the entire northern Australia, revealing the existence of high pest and resistance pressure (to fumigant, phosphine) in selected grain storage sites. RFB infestations were more prevalent in the region, followed by LGB or RGB. A large number of insects were trapped in the region during both seasons: wet summer and dry winter, indicating the importance of adopting preventive control measures on time. The observed resistance percentage in RFB in the north is relatively higher than the average resistance percentage values reported for the southern region. This could be due to two major reasons: 1. the warm and humid conditions of the tropics favouring rapid multiplication and spread of resistant insect populations and 2. lack of awareness on managing pests and resistance on time. Thus, proper monitoring or management strategies are essential for the northern region towards reducing the overall pest pressure and preventing the risk of selecting resistant populations further. Moreover, the lack of monitoring and region-specific pest control programs creates loopholes for the easy establishment of new biosecurity incursions. For instance, since most of the cereal grains are used for the domestic stock feed market in the north, routine phosphine fumigations can be swapped for a registered grain protectant mixture. Sulfuryl fluoride, a break fumigant, can also be used in rotation with phosphine for controlling phosphine-resistant populations. Considering these contexts, the following Integrated Pest and Resistance Management (IPRM) strategies are recommended for the industry.

- **Structural integrity:** Scientific storage starts with the right structure, and it is recommended that growers and stakeholders opt for gas-tight silos that meet the Australian standards AS2628-2010 for pressure testing. The required half-life of the pressure test is 3 to 5 minutes.
- **Storage Hygiene:** Maintaining high-level hygiene at the storage site is the first line of defence in protecting freshly harvested grains. Keeping grain storage areas clean and free from spills and split grains reduces the chances of hidden insect populations onsite. Similarly, cleaning headers, chaser bins, augers, and trucks before and after harvest prevents insect carryovers. Thus, adhering to routine hygiene onsite eliminates insect breeding sites and pest rebounds which could assist growers in avoiding costly quality downgrades.
- **Pest monitoring:** Regular monitoring of grain for insect pests is paramount. Various traps (probe, dome, or Lindgren funnels) along with the physical screening of grain samples from the hopper could assist in the early detection of the insect species and their infestation levels. This not only helps in implementing suitable control measures early but also minimizes costly delays at the time of delivery.
- **Resistance testing:** Storage insect populations in Australia, include insects with weak and strong resistance to phosphine, so diagnosing resistance levels in local insect populations ensures the adoption of the correct dose rate that avoids the recurrence of resistant insects onsite. The test insect samples along with the small batch of infested grains can be sent to the DPI regional office by post for diagnosis. Though this process requires substantial time, the information generated could provide site-specific meaningful insights towards managing resistant insect populations regionally. Implementation of such strategies could also be helpful for the entire north.

- **Aeration:** Although aeration cooling of grains is challenging for the north, an automated aeration fan set- with the required airflow rate can still be used to reduce the grain temperature in summer. Cooling grains below 25°C hinders the rapid multiplication of many grain insect pests in the infested commodity and reduces control filatures and the frequency of using chemical treatments.
- **Structural treatments:** Diatomaceous Earth (DE) on concrete and steel surfaces was not very effective against two major grain insect pests, RFB and SGB. Higher humidity and species-specific variations in tolerance are attributed to this, we believe more field research accommodating variables such as evenness of DE, and humidity levels inside the storage structure could provide practical insights. Alternatively, a specific formulation of a synthetic pyrethroid, deltamethrin is also registered and available for treating storage structures. This can be used on concrete and steel structures, though, more information on its efficacy and application needs to be generated and standardized.
- **Grain protectant:** The triplet grain protectant combo, SCS is very effective against multiple populations of grain insect species tested, including, RFB, RW, LGB, MW and RGB at high temperatures (35°C) and humid (75%) conditions. This is great news for the industry, as this mixture can be used for treating feed grain and planting seeds in storage structures that are not gas-tight. The mixture, SCS is registered for cereal grains only and not for pulses and oilseeds, thus always follow the label instructions and check with buyer or market requirements before use.
- **Fumigants:** The current phosphine label rate over a 7day exposure period is effective at 25°C and above, though strongly resistant RGB, and eggs of BDS, required higher concentrations (720 ppm) over a longer exposure period (up to 10 days) for complete control. Alternatively, one-third of the maximal registered label rate of SF, 500 g hm^{-3} can be used over an exposure period of 5 days for controlling these challenging insect species including phosphine-resistant populations. Care should be undertaken not to perform quick high-dose SF fumigations over short fumigation periods (48 hrs.), as these fumigations most likely select insect life stages (e.g. eggs) for increased tolerance or genetic resistance in the long run. SF is also not registered for treating pulses and oilseeds, therefore, organic fume treatments such as carbon-di-oxide or nitrogen can be followed in selective scenarios, though these treatments are usually cost-prohibitive in comparison to phosphine and SF.

Expected outcomes:

The project contained the following expected outcomes:

1. Improved pest and resistance management in northern Australia: Achieving this outcome will reduce postharvest losses and enhance the quality of the grain produced in this region. This will allow the effective functioning of the local grain supply chain as well as provide direct access to the international grain trade. The adoption of science-based management practices will reduce the rate of resistance development (phosphine) and safeguard the use of alternatives (sulfuryl fluoride). Further, the additional cost of insect infestation and remedial treatments at the port can be avoided.

2. Improved local capacity on scientific grain storage: The project aims to enhance the knowledge and skills of various participants and end-users involved in grain storage, insect pest and resistance management, including local trainees and students. Investing in a new generation of scientists and technicians in ecological and toxicological techniques and their application to ecology and pest management will more effectively address future food security needs.

3. Awareness of invasive threats: Knowledge of the basics of pest diagnostics and an improved understanding of biosecurity threats and their implications on the export market will make northern Australia resilient to pest incursions.

4. Research-extension and end-user alliance: The project will provide the perfect platform for developing an alliance between various professionals involved in grain protection. This region-specific linkage or association may provide better insight into research priorities and development. This will pave the way for future collaborative research projects and the delivery and adoption of research outputs.

Successful adoption of the outcomes of this project, together with industry support, will ensure that the grain quality meets domestic and international market standards and likely result in significant additional investments promoting regional business and development. While the Townsville port is under expansion, with companies establishing their base, the key outputs delivered through this project are timely as it will facilitate rerouting the supply chain through the Brisbane port, thereby reducing transport costs involved at several stages. This

systemic change, along with other improvements in post-farm processing and marketing, should increase profit margins across the community and contribute to the sustained increase in the GDP of northern Australia.

Strategic recommendations

Key priority actions for sector development	Action owner and key partners	Pathways to implementation and timeline	Intended industry impacts
Implementing scientifically sound grain storage structures that are suitable for the northern tropics **Adopt region-specific and information-based pest intervention strategies rather than calendar-based routine tasks**	Growers and the industry stakeholders of the region should carefully review the products available in the market and ensure that the structures meet Australian standards. They also request assistance from the marketing companies and extension agronomists and ensure that the storage structures are installed properly and functioning. Growers and other industry stakeholders utilize basic pest monitoring tools and the established project information / key findings for different scenarios in consultation with regional DPI extension professionals	Though grain storage across the northern region is still at its early stage, the problem of pests and resistance is serious and requires immediate interventions. The regional transformation will likely happen in the next 2-3 years and could attract significant additional investments promoting regional business and development.	Successful adoption of the outcomes of this project, together with industry support, will ensure that the growers and the industry maintain the grain quality, meeting the requirements of domestic and international markets. The exact percentage of grains and pulses produced in northern Australia is not readily available, but the contribution from these regions, northern QLD, NT and northern WA, is substantial and plays a vital role in overall Australian grain export worth AU$ 28.9 billion (GRDC, 2025). “Adopting scientific grain storage in rotation with sugarcane cropping increases the farm profitability up to $2000/ha/year. Overall successful transformation brings substantial trade benefits contributing to GDP growth and supporting several employments in the food and processing sector and secures to the national wellbeing.

Acknowledgement:

Sizer and Cogill Australia Limited

Home hill stock feeds

Several lead growers

Kondinin group, Western Australia

Primary Business, South Australia

Silo manufacturers (Grain Masters, Dennys)

Agronomist and Farmacist (Elders, Nutrient Ag)

References

[1] FAO (1975). Recommended methods for the detection and measurement of resistance of agricultural pests to pesticides: tentative method for adults of some major species of stored cereals with methyl bromide and phosphine—FAO Method No 16. FAO Plant Prot. Bull. 23:12–25

[2] Daglish, G and Nayak, M (2006) Long-term persistence and efficacy of spinosad against *Rhyzopertha dominica* (Coleoptera: Bostrychidae) in wheat. Pest Management Science, 62 (2): 148-152

[3] Collins, P.J., Nayak, K.M and Kopitke, R.A (2000). Residual Efficacy of Four Organophosphate Insecticides on Concrete and Galvanized Steel Surfaces Against Three Liposcelid Psocid Species (Psocoptera: Liposcelidae) Infesting Stored Products. Journal of Economic Entomology 93(4):1357-63

[4 Ridley, A.W., Hereward, J.P., G. J. Daglish, S. Raghu, G. A. McCulloch, and G. H. Walter (2016). Flight of *Rhyzopertha dominica* (Coleoptera: Bostrichidae)—a Spatio-Temporal Analysis With Pheromone Trapping and Population Genetics. Journal of economic entomology, 109 (6): 2561-2571

Appendices

Table 1. List of grain insect pests identified in multiple grain samples collected from farms based at Townsville, Queensland (Home hill, Ayre, and Mona Park). The samples were collected over two seasons, May to September 2022 and October 2022 to September 2023, and screened in the laboratory.

Farm No.	Lesser Grain Borer		Rice Weevil		Red Flour Beetle		Rusty Grain Beetle		Maize Weevil		Bruchids		Sawtooth Grain Beetle		Book Lice*
	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Population
1	2	11	1	4	3	130	3	300	0	0	0	0	0	0	2
2	0	0	0	0	1	10	1	11	1	6	1	3	0	0	0
3	0	0	0	0	1	6	0	0	0	0	0	0	0	0	0
4	0	0	1	20	0	0	1	22	0	0	0	0	0	0	0
5	0	0	0	0	1	6	0	0	0	0	0	0	0	0	0
6	0	0	0	0	2	310	0	0	0	0	0	0	0	0	2
7	0	0	0	0	0	0	1	53	0	0	0	0	0	0	0
8	0	0	1	2	1	53	0	0	0	0	0	0	0	0	0
9	1	14	1	100	4	80	2	123	1	100	0	0	0	0	0
10	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
11	0	0	0	0	2	58	0	0	0	0	0	0	0	0	0
12	0	0	0	0	5	574	1	2	0	0	0	0	0	0	1
13	1	18	0	0	0	0	1	100	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	1	1000	0	0	0	0	0
15	0	0	0	0	1	4	0	0	1	16	0	0	0	0	0
16	2	140	2	23	1	4	2	68	1	1	0	0	0	0	0
17	1	3	1	100	5	59	4	105	0	0	0	0	0	0	0
18	1	2	0	0	1	34	1	5	0	0	0	0	0	0	0
19	1	120	0	0	1	120	0	0	1	200	0	0	0	0	0
20	0	0	2	7	1	1	1	78	1	46	0	0	0	0	0
21	1	4	0	0	1	3	1	3	0	0	0	0	0	0	0
22	2	19	0	0	0	0	1	23	0	0	0	0	0	0	0
23	2	40	3	26	3	23	2	5	1	300	0	0	0	0	0
24	2	13	0	0	2	3	0	0	2	178	0	0	0	0	0
25	0	0	0	0	2	6	0	0	0	0	0	0	0	0	0
26	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	2	501	0	0	0	0	0	0	0
28	0	0	1	15	2	250	2	122	0	0	0	0	0	0	0
29	0	0	0	0	3	41	1	35	0	0	0	0	0	0	0
30	0	0	0	0	2	13	1	2	1	13	0	0	0	0	0
31	0	0	1	100	1	60	0	0	0	0	0	0	0	0	0

32	0	0	0	0	1	500	1	22	0	0	0	0	0	0	0
33	0	0	0	0	1	18	1	25	1	35	0	0	1	8	0
34	0	0	0	0	1	3	0	0	0	0	2	14	0	0	0
35	0	0	0	0	2	1029	0	0	0	0	1	17	0	0	0
36	1	15	1	82	0	0	1	5	0	0	0	0	0	0	0
37	0	0	0	0	1	4	0	0	0	0	3	9	0	0	0
38	0	0	0	0	1	145	0	0	0	0	0	0	0	0	0
39	0	0	1	200	1	200	1	1000	0	0	0	0	0	0	0
40	0	0	0	0	2	1500	1	1000	1	1000	0	0	0	0	0
41	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
42	3	177	1	4	3	47	1	25	0	0	3	347	0	0	0
43	0	0	0	0	0	0	0	0	1	48	0	0	0	0	0
	20	**576**	**17**	**683**	**63**	**5300**	**34**	**3635**	**14**	**2943**	**10**	**390**	**1**	**8**	**5**

The samples collected from two farm sites, #44 and #45 are free from insect infestations.

Lesser Grain Borer (**LGB)**, *Rhyzopertha dominica*, Rice Weevil (**RW**), *Sitophilus oryzae*, Red Flour Beetle (**RFB**), *Tribolium castaneum*, Rusty Grain Beetle (**RGB**), *Cryptolestes ferrugineus* Maize Weevil (**MW**), S*itophilus zeamais;*Bruchids (**BDS**), *Callasobruchus maculatus;* Sawtooth Grain Beetle (**SGB**), (*Oryzaephilus surinamensis*) ; Booklice / Psocids (**BL**), *Liposcelis botrychophila;*

*Insect populations could not be established for this pest species.

Total number of insect species established for the region, Townsville in northern Queensland: 13 + 19 + 59 + 33 + 9 + 12 + 1 = **146**

Table 2. List of insect pests identified in grain samples collected from farms in and around MacKay, Queensland. The samples were collected in June 2022 and screened in the laboratory.

Farm No.	Rice Weevil		Red Flour Beetle		Rusty Grain Beetle		Lesser Grain Borer		Sawtooth Grain Beetle		Book Lice*
	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Population
46	1	14	1	100	0	0	0	0	0	0	1
47	1	100	1	19	1	14	0	0	0	0	0
48	0	0	1	100	1	60	1	50	0	0	0
49	0	0	0	0	0	0	0	0	1	20	1
	2	**114**	**3**	**219**	**2**	**74**	**1**	**50**	**1**	**20**	**2**

The samples collected from two farm sites, #50 and #51 are free from live insect infestations.
Rice Weevil (**RW**), *Sitophilus oryzae*,
Red Flour Beetle (**RFB**), *Tribolium castaneum*,
Rusty Grain Beetle (**RGB**), *Cryptolestes ferrugineus*
*population couldn't be established in the laboratory for this species
Total number of insect populations established for the region MacKay in northern Queensland: 2 + 2 + 1 = 4

Table 3. List of insect pests identified in grain samples collected from farms in and around Cairns (Richmond/Atherton Tablelands), Queensland. The samples were collected in July 2023 and screened in the laboratory.

Farm No.	Lesser Grain Borer		Rice Weevil		Red Flour Beetle		Rusty Grain Beetle		Sawtooth Grain Beetle		Maize Weevil	
	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers
52	0	0	1	1000	1	2	0	0	0	0	1	3
53	2	215	4	151	1	2	0	0	2	43	0	0
54	0	0	0	0	1	2	1	58	0	0	1	500
55	2	102	0	0	2	52	1	1	0	0	0	0
56	1	100	0	0	1	100	1	19	0	0	0	0
57	1	1	0	0	1	3	0	0	0	0	0	0
	6	**418**	**5**	**1151**	**7**	**161**	**3**	**78**	**2**	**43**	**2**	**503**

Lesser Grain Borer (**LGB**), *Rhyzopertha dominica*,
Red Flour Beetle (**RFB**), *Tribolium castaneum*,
Rusty Grain Beetle (**RGB**), *Cryptolestes ferrugineus*
Sawtooth Grain Beetle (**SGB**), (*Oryzaephilus surinamensis*)
Maize Weevil (**MW**), S*itophilus zeamais*
Bruchids (**BDS**), *Callasobruchus maculatus*
Total number of insect populations established for the region Cairns in northern Queensland: 6 + 8 + 11 + 3 + 3 + 2 + 1 = 34

Table 4. List of insect pests identified in grain samples collected from farms based at Kununurra and Broome in northern Western Australia. The samples were collected between August 2022 to August 2023 and screened in the laboratory.

Farm No.	Red Flour Beetle		Rusty Grain Beetle		Sawtooth Grain Beetle		Lesser Grain Borer	
	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers
58	0	0	0	0	0	0	1	46
59	0	0	0	0	0	0	1	2
60	1	2	0	0	0	0	0	0
61	2	7	1	7	5	29	0	0
62	2	61	0	0	0	0	0	0
63	2	147	0	0	0	0	0	0
64	4	38	0	0	0	0	0	0
65	2	10	0	0	0	0	0	0
66	1	1	0	0	0	0	0	0
	14	**266**	**1**	**7**	**5**	**29**	**2**	**48**

The samples collected from two farm sites, #67 and #68 are free from live insect infestations.
Red Flour Beetle (**RFB**), *Tribolium castaneum*,
Rusty Grain Beetle (**RGB**), *Cryptolestes ferrugineus*
Sawtooth Grain Beetle (**SGB**), (*Oryzaephilus surinamensis*)
Lesser Grain Borer (**LGB)**, *Rhyzopertha dominica*
Total number of populations established in nWA: 14 + 2 + 5 + 2 = 23

Table 5. List of insect pests identified in grain samples collected from farms based at Darwin and Tortilla Flat in Northern Territory. The samples were collected between August 2022 to August 2023 and screened in the laboratory.

Farm No.	Lesser Grain Borer		Rice Weevil		Red Flour Beetle		Rusty Grain Beetle		Sawtooth Grain Beetle		Bruchids	
	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers	Number of Populations	Insect Numbers
69	1	17	0	0	3	12	2	18	1	3	1	1
70	3	25	0	0	0	0	2	9	2	11	1	3
71	3	24	0	0	3	26	1	5	1	8	0	0
72	0	0	0	0	1	Blank	0	0	0	0	0	0
73	3	80	0	0	3	21	0	0	1	2	0	0
74	1	70	0	0	1	67	0	0	0	0	0	0
75	2	62	0	0	2	35	1	92	1	30	0	0
76	1	97	2	72	0	0	2	38	1	6	0	0
77	2	11	0	0	4	75	1	3	1	1	0	0
78	2	13	0	0	2	96	0	0	1	5	0	0
79	1	25	0	0	3	59	0	0	3	1044	0	0
80	0	0	0	0	2	188	0	0	0	0	0	0
	19	**424**	**2**	**72**	**24**	**579**	**9**	**165**	**12**	**1110**	**2**	**4**

Lesser Grain Borer (**LGB)**, *Rhyzopertha dominica*,
Rice Weevil (**RW**), *Sitophilus oryzae*,
Red Flour Beetle (**RFB**), *Tribolium castaneum*,
Rusty Grain Beetle (**RGB**), *Cryptolestes ferrugineus*
Sawtooth Grain Beetle (**SGB**), (Oryzaephilus surinamensis)
Bruchids (**BDS**), *Callasobruchus maculatus*
Total number of populations established in NT: 17 + 1 + 28 + 9 +10 + 2 = 67

Table 6. Per cent resistance to fumigant, phosphine in key grain insect pests collected from storage sites located within the Townsville region in northern Queensland (nQLD).

Insect species	Total number of populations tested	Phenotype diagnosed			Weak Resistance (%) (Range[c])	Strong Resistance (%) (Range[c])
		Susceptible	Weakly resistant[a]	Strongly Resistant[b]		
LGB	15	0	10	5	15-97	2-88
RFB	55	4	21	30	1-65	1-100
RGB	25	0	10	15	35-97	1-99
RW	11	1	7	3	1-73	0-3
MW	13	2	11	0	0-86	0
SGB	2	2	0	0	0	0

Table 7. Per cent resistance to fumigant, phosphine in key grain insect pests collected from storage sites located within the MacKay region in northern Queensland (nQLD).

Insect species	Total number of populations tested	Phenotype diagnosed			Weak Resistance (%) (Range[c])	Strong Resistance (%) (Range[c])
		Susceptible	Weakly resistant[a]	Strongly Resistant[b]		
LGB	1	0	0	1	74	9
RFB	3	1	2	0	0-24	0
RGB	1	0	1	0	14	0
RW	2	0	2	0	1-15	0
SGB	1	1	0	0	0	0

Table 8. Per cent resistance to fumigant, phosphine in key grain insect pests collected from storage sites located within the Cairns region in northern Queensland (nQLD).

Insect species	Total number of populations tested	Phenotype diagnosed			Weak Resistance (%) (Range[c])	Strong Resistance (%) (Range[c])
		Susceptible	Weakly resistant[a]	Strongly Resistant[b]		
LGB	5	0	4	1	76-97	2
RFB	5	0	3	2	5-16	7-100
RGB	2	0	2	0	62-85	0
RW	3	0	3	0	47-64	0
MW	2	0	2	0	19-32	0
SGB	1	0	1	0	4	0

Table 9. Per cent resistance to fumigant, phosphine in key grain insect pests collected from storage sites located within Kununurra and Broome regions in northern Western Australia (nWA).

Insect species	Total number of populations tested	Phenotype diagnosed			Weak Resistance (%) (Range[c])	Strong Resistance (%) (Range[c])
		Susceptible	Weakly Resistant[a]	Strongly Resistant[b]		
LGB	1	0	1	0	99	0
RFB	12	0	1	11	27	4-95
RGB	1	0	1	0	15	0
SGB	3	0	3	0	5-33	0

Table 10. Per cent resistance to fumigant, phosphine in key grain insect pests collected from storage sites located within Darwin and Tortilla Flat regions in Northern Territory (NT).

Insect species	Total number of populations tested	Phenotype diagnosed			Weak Resistance (%) (Range[c])	Strong Resistance (%) (Range[c])
		Susceptible	Weakly Resistant[a]	Strongly Resistant[b]		
LGB	15	0	13	2	49-99	2-8
RFB	24	0	5	19	3-60	1-82
RGB	5	0	5	0	26-83	0
SGB	8	3	5	0	0-98	0

Lesser Grain Borer (LGB), *Rhyzopertha dominica*, Red Flour Beetle (RFB), *Tribolium castaneum*, Rusty Grain Beetle (RGB), *Cryptolestes ferrugineus* Rice Weevil (RW), *Sitophilus oryzae*

[a]Insects were exposed to phosphine at 0.03 mg l^{-1} over 20 hrs

[b]Insects were exposed to phosphine at 0.25 mg l^{-1} over 20 and 48 hrs exposure periods for RFB, and LGB, respectively. For RGB, test insects were exposed to 1mg l^{-1} over 168 hrs.

[c]Values within the parenthesis represent minimum and maximum per cent resistance values recorded among the multiple populations tested.

Table 11. Efficacy of phosphine (PH_3) against mixed-age populations of resistant rice weevil (RW), *Sitophilus oryzae* at 30 °C and 70% RH.

Insect species[a]	Strain[b]	Dose (mg L^{-1})	Exposure period (Days)	C x T (gh m^{-3})[c]	Adult mortality (%)[d]	Progeny Mortality (%)[e]
Sitophilus oryzae	PH_3-R_1	0.3	6	43.2	100	100
		0.3	7	50.4	100	100
		1	4	96	100	100

[a]Results shown are preliminary and involve limited replications. More experiments are in progress.
[b]PH_3-R_1: phosphine-resistant reference strain
[c]Tested CT products are within the maximum approved label rates (168 g hm^{-3}) for PH_3.
[d]Mortality assessment carried out immediately after the termination of the fumigation bioassay.
[e]Mortality assessment carried out 6-8 weeks after the termination of fumigation bioassay, targeting to capture the response of immature insect life stages.

Table 12. Dose mortality response of adults of three key grain insect pests, the rice weevil, *Sitophilus oryzae*, the maize weevil, *Sitophilus zeamais*, and the cowpea bruchids, *Callosobruchus maculates* to phosphine (PH_3) at 25°C over an 20 h exposure period for *S. oryzae* and *S. zeamais* and 24h period for *C. maculatus*.

Insect species	Strain	LC_{50} (mg L^{-1}) FL[a]	$LC_{99.9}$ (mg L^{-1}) FL[b]
Sitophilus oryzae	Lab-S	0.0082 (0.008–0.009)	0.030 (0.027–0.035)
Sitophilus zeamais	Field-SZ_1	0.008 (0.005- 0.011)	0.13 (0.05- 7.07)
	Field -SZ_2	0.007 (0.006- 0.009)	0.07 (0.04- 0.21)
Callosobruchus maculatus	Field-CM_1	0.02 (0.01- 0.03)	0.22 (0.10- 2.01)
	Field-CM_2	0.02 (0.01- 0.03)	0.19 (0.10- 0.98)

[a]LC: Lethal Concentrations
[b]FL: Fiducial Limits

Table 13. Effectiveness of the discriminating dose of sulfuryl fluoride (SF), 1.70 mg L^{-1} over 48 hours in multiple reference strains and field populations of red flour beetle, *Tribolium castaneum*.

Strain /Population	Total number of insects tested	Mortality (%)	
		Control	Treated
Lab-S	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_1	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_2	200	0.0 ± 0.0	100 ± 0.0
SP-R_3	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_4	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_5	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_6	200	0.0 ± 0.0	100 ± 0.0
PH_3-R_7	200	0.0 ± 0.0	100 ± 0.0
Field -1	200	0.0 ± 0.0	100 ± 0.0
Field-2	200	0.0 ± 0.0	100 ± 0.0
Field-3	200	0.0 ± 0.0	100 ± 0.0
Field-4	200	0.0 ± 0.0	100 ± 0.0

Lab-S: Laboratory reference strain that is susceptible to phosphine (PH_3) and other contact insecticides.
PH-R: Phosphine-resistant reference strain, SP- Synthetic Pyrethroid resistant strain
Field: Field collected insect population

Table 14. Efficacy of sulfuryl fluoride (SF) against mixed-age populations of three key grain insect pests, the rice weevil (RW), *Sitophilus oryzae*, the maize weevil (MW), *S. zeamais*, and the bruchids (BDS), *Callosobruchus maculates* at 30 °C and 70% RH.

Insect species[a]	Strain[b]	Dose (mg L^{-1})	Exposure period (Days)	C x T (gh m^{-3})[c]	Adult mortality (%)[d]	Progeny Reduction (%)[e]
Sitophilus oryzae	PH_3-R_1	1.78	7	300	100	100
		3.33	10	800	100	100
Sitophilus zeamais	Field-SZ_1	0.5	2	24	93.6	55.4
		1	2	48	100	75.5
		2	2	96	100	74.24
		4	2	192	100	99.99
		0.5	4	48	100	74.9
		1	4	96	100	95.0
		2	4	192	100	97.9
		4	4	384	100	100
		4.5	7	756	100	100
		4.5	10	1080	100	100
Callosobruchus maculatus	Field-CM_1	2	2	96	100	100
		4	2	192	100	100
		6	2	288	100	100
		2	4	192	100	100
		4	4	384	100	100
		6	4	576	100	100
		4	4	384	100	100
		6	4	576	100	100
		8	4	768	100	100
		8	6	1152	100	99.9
		2	7	336	100	100
		3	7	504	100	100
		3.5	7	756	100	100
		4	7	672	100	100

[a]Some of the results shown contained limited replicated data, and confirmatory experiments are in progress.
[b]PH_3-R_1: phosphine resistant reference strain; Field: recently collected insect population from the field.
[c]Tested CT products are within the maximum approved label rates (1500 g hm^{-3}) for SF.
[d]Mortality assessment carried out immediately after the termination of the fumigation bioassay.
[e]Mortality assessment carried out 6-8 weeks after the termination of fumigation bioassay, targeting to capture the response of immature insect life stages.

Table 15. Dose mortality response of adults of three key grain insect pests the rice weevil (RW), *Sitophilus oryzae*, the maize weevil (MW), *S. zeamais*, and the bruchids (BDS), *Callosobruchus maculates* to sulfuryl fluoride over 48h at 25°C.

Insect species	Strain[a]	LC_{50} (mg L^{-1}) FL[b]	$LC_{99.9}$ (mg L^{-1}) FL[c]
Sitophilus oryzae	PH_3-R_2	0.56 (0.55- 0.58)	0.78 (0.72- 0.87)
Sitophilus zeamais	Field-SZ_1	0.56 (0.50- 0.61)	1.5 (1.23- 2.31)
	Field -SZ_2	0.48 (0.42- 0.53)	1.05 (0.86- 1.64)
	Field-SZ_3	0.36 (0.28- 0.41)	1.03 (0.82- 1.77)
Callosobruchus maculatus	Field-CM_1	0.42 (0.42- 0.42)	0.46 (0.46- 0.46)
	Field-CM_2	0.48 (0.47- 0.50)	0.76 (0.71- 0.85)

[a]PH_3-R_1: phosphine resistant reference strain; Field: recently collected insect population from the field.
[b]LC: Lethal concentrations
[c]FL- Fiducial Limits

Table 16. Effectiveness of grain protectant (triplet treatment, Spinosad 100 g/L + Chlorpyriphos-methyl 500 g/L + s Methoprene 100 g/L) against several insect populations collected from nQLD, NT, and nWA. The bioassays were carried out at 35°C and 70% RH, representing the regional climatic conditions.

Region	Pest Species tested[a]	No. of Populations Tested 2022-2023	No. of Populations Tested 2023-2024	Mortality (%)	
				Adults[b]	Progeny[c]
nQLD	LGB	1	1	100*	100*
	RFB	1	8	100*	100*
	RGB	1	2	100*	100*
	RW	1	-	100	100
	MW	1	-	100	100
NT	LGB	1	-	100	100
	RFB	1	-	100	100
	SGB	1	-	100	100
nWA	RFB	1	-	100	100
	SGB	1	-	100	100
Total number of populations		**10**	11		

[a]Reference insect populations established from healthy insect samples collected from multiple storage sites within each state/region.
[b]Adult insects two weeks after eclosion were challenged with treated grain and maintained at high temperature (35°C) and humidity (75%) mortality was recorded after 14 days.
[c]Effectiveness against immature life stages, eggs, larvae, and pupae of parental adults (F_1) was estimated in comparison to the number of freshly emerged adults in the untreated control.
*Mortality range observed across multiple populations investigated during the year 2022-2024

Table 17. Effectiveness of diatomaceous earth, DE (at the rate of 2g m^2) in concrete surfaces against several insect populations collected from nQLD, NT, and nWA. The bioassays were carried out at 35°C and 70% RH representing the regional climatic conditions.

Region	Pest Species tested[a]	No. of Populations Tested 2022-2023	No. of Populations Tested 2023-2024	Mortality (%)[b]
nQLD	LGB	1	-	100
	RFB	**1**	**8**	54.7 ± 7.5 - 100*
	RGB	1	2	100
	RW	1	1	100
	MW	1	-	100
NT	LGB	1	-	100
	RFB	1	-	59.8 ± 14.2
	SGB	1	-	100
nWA	RFB	**1**	-	94.0 ± 3.1
	SGB	1	-	99.2 ± 0.8
Total number of populations		10	11	

[a]Reference insect populations established from healthy insect samples collected from multiple storage sites within each state/region.
[b]Adult insects two weeks after eclosion were released into treated concrete surfaces and the set up was placed at a high temperature (35°C) and humidity (70%). The mortality in both treated and untreated experiments was recorded after 14 days.
*Mortality range observed across the nine populations (1 in year 2022 and 8 in 2023) investigated (refer to Table 17 for more details)

Table 18. Effectiveness of diatomaceous earth, DE (at the rate of 2g m^2) in concrete surfaces against nine red flour beetle (8 in 2023-24 and 1 in 2022-2023) insect populations collected from nQLD. The bioassays were carried out at 35°C and 70% RH representing the regional climatic conditions.

Region	Pest Species tested[a]	Populations Tested 2022-2023	Mortality (%)[b]
nQLD	RFB	1	54.75 ± 7.5
		2	100
		3	100
		4	92.6 ± 1.3
		5	100
		6	98.6 ± 1.4
		7	80.3 ± 15.8
		8	95.8 ± 4.2
		9	100
	RGB	1	100
		2	100
Total number of populations		11	

[a]Reference insect populations established from healthy insect samples collected from multiple storage sites within each state/region.
[b]Adult insects two weeks after eclosion were released into treated concrete surfaces and the set up was placed at a high temperature (35°C) and humidity (70%). The mortality in both treated and untreated experiments was recorded after 14 days.

Table 19. Effectiveness of diatomaceous earth, DE (at the rate of 2g m^2) in steel surfaces against several insect populations collected from nQLD. The bioassays were carried out at 35°C and 70% RH representing the regional climatic conditions.

Region	Pest Species tested[a]	No. of Populations Tested 2022-2023	No. of Populations Tested 2023-2024	Mortality (%)[b]
nQLD	RFB	1	-	94.5 ± 2.7
		2	-	100
		3	-	100
	LGB	1	-	100
	RGB	1	1	100
NT	SGB	-	1	100
WA	RFB	-	1	26 ± 0.1
Total number of populations		5	3	-

[a]Reference insect populations established from healthy insect samples collected from multiple storage sites within each state/region.
[b]Adult insects two weeks after eclosion were released into treated concrete surfaces and the set up was placed at a high temperature (35°C) and humidity (70%). The mortality in both treated and untreated experiments was recorded after 14 days.

Table 20. The abundance of five major grain pest species across three trap types at six sites over 13 months of the trapping program. The insect numbers for the dome traps represent the average of two traps (n=2).

(*a*) Pheromone-baited Dome traps

Season	Month	LGB	RFB	RW	RGB/FGB	MGB	Total
		R. dominica	*T. castaneum*	*S. oryzae*	*Cryptolestes* spp.	*O. mercator*.	
Dry season	Oct-22	1	18	3.5	0	1.5	24
Wet season	Nov-22	14.5	40	8.5	0	0.5	63.5
	Dec-22	0.5	286	136	5.5	0.5	428.5
	Jan-23	2	190	37.5	4	0.5	234
	Feb-23	0	211	13.5	28	0.5	253
	Mar-23	1	318.5	10.5	7	0	337
	Apr-23	2	514	12.5	1.5	0	530
Dry season	May-23	3	549	19.5	9	0.5	581
	Jun-23	0.5	402.5	160	6	0	569
	Jul-23	2	866	194	1.5	0	1063.5
	Aug-23	0	976	594	2	0	1572
	Sep-23	0.5	1056.5	190	0	0	1247
	Oct-23	0	831.5	668	0	0	1499.5
Wet season	Nov-22	0	468	1347.5	0	0	1815.5
	Dec-22	0	623.5	490.5	0	0	1114
	Jan-23	0.5	562	159.5	0	0	722
	Feb-23	1	217.5	0	27.5	0	246
	Total	28.5	8130	4045	92	4	12299.5

(*b*) Pheromone-baited Lindgren funnel traps

Season	Month	LGB	RFB	RW	RGB/FGB	MGB	Total
		R. dominica	*T. castaneum*	*S. oryzae*	*Cryptolestes* spp.	*O. Mercator*	
Dry season	Oct-22	2315	259	33	70	1	2678
Wet season	Nov-22	1659	161	43	193	0	2056
	Dec-22	1221	320	53	90	0	1684
	Jan-23	339	131	1	146	0	617
	Feb-23	65	44	0	15	0	124
	Mar-23	42	140	0	32	0	214
	Apr-23	168	166	0	12	0	346
Dry season	May-23	2438	75	0	0	0	2513
	Jun-23	233	41	0	13	0	287
	Jul-23	296	58	0	10	0	364
	Aug-23	28	29	0	0	0	57
	Sep-23	94	54	5	2	0	155
	Oct-23	185	113	64	0	0	362
Wet season	Nov-22	764	231	107	3	0	1105
	Dec-22	453	178	34	7	0	672
	Jan-23	282	207	26	55	0	570
	Feb-23	100	122	16	2	0	240
	Total	10682	2329	382	650	1	14044

(*c*) Unbaited Lindgren funnel traps

Season	Month	LGB	RFB	RW	RGB/FGB	MGB	Total
		R. dominica	*T. castaneum*	*S. oryzae*	*Cryptolestes* spp.	*O. mercator*	
Dry season	Oct-22	32	13	3	4	1	53
Wet season	Nov-22	29	21	7	12	0	69
	Dec-22	13	22	1	0	0	36
	Jan-23	1	3	0	2	0	6
	Feb-23	0	3	0	3	0	6
	Mar-23	0	4	0	95	0	99
	Apr-23	48	56	0	2	0	106
Dry season	May-23	5	12	0	0	0	17
	Jun-23	0	1	6	9	0	16
	Jul-23	4	3	4	0	0	11
	Aug-23	0	1	5	2	0	8

	Sep-23	0	4	6	0	0	10
	Oct-23	3	9	5	0	0	17
Wet season	Nov-22	0	2	7	4	0	13
	Dec-22	5	0	1	0	0	6
	Jan-23	5	20	2	4	0	31
	Feb-23	0	1	3	0	0	4
	Total	145	175	50	137	1	508

Lesser Grain Borer (**LGB)**, *Rhyzopertha dominica*, Red Flour Beetle (**RFB**), *Tribolium castaneum*, Rusty Grain Beetle (**RGB**) or Flat Grain Beetle (F**GB**), *Cryptolestes* spp, Rice Weevil (**RW**), *Sitophilus oryzae* and, Merchant Grain Beetle (**MGB**), *Oryzaephilus Mercator*

Table 21. Efficacy of phosphine (PH_3) fumigation performed in a 168m^3 tonne steel silo based at Home hill, Ayre, northern Queensland. The silo contained 130 tonnes of sorghum grains and mixed insect life stages of four insect species confined in steel cages, red flour beetle, RFB, rusty grain beetle, (RGB), rice weevil (RW) and the Bruchids (BDS) at different depths. The target concentration of the fumigation was 1g m^{-3} over 7 days and both adult mortality and per reduction in progeny were provided below.

Species	Location	Adult mortality (%)	Cumulative progeny numbers emerged	Progeny reduction (%)
RFB	Control	9.2 ± 0.04	1 ± 1.000	-
	Top	100	0	100
	Bottom	100	0	100
RGB	Control	2.7 ± 0.0	356.3 ± 63.8	-
	Top	91.9 ± 0.0	124.0 ± 2.0	65
	Bottom	71.4 ± 0.05	70.5 ± 0.5	80
RW	Control	8.9 ± 0.02	191. 7 ± 15.6	-
	Top	100	0	100
	Bottom	100	0	100
BDS	Control	61.3 ± 0.18	2928 ± 139.6	-
	Top	100	3.33 ± 1.73	99.89
	Bottom	100	1.00 ± 0.58	99.97

Table 22. Efficacy of sulfuryl fluoride (SF) fumigation performed in a 344m^3 tonne steel silo based at Townsville, northern Queensland. The silo contained 250 tonnes of sorghum grains and mixed insect life stages of four insect species confined in steel cages, red flour beetle, RFB, rusty grain beetle, (RGB), rice weevil (RW) and the Bruchids (BDS) at different depths. The target concentration of the fumigation was 500g hm^{-3} over 5 days and both adult mortality and per reduction in progeny were provided below.

Species	Location	Adult mortality (%)	Cumulative progeny numbers emerged	Progeny reduction (%)
RFB	Control	1.58 ± 0.0	0*	-
	Top	100	0*	0
	Bottom	100	0	0
RGB	Control	4.02 ± 0.0	17.7 ± 5.7	-
	Top	100	0	100
	Bottom	100	0	100
RW	Control	37.80 ± 0.04	108.3 ± 25.6	-
	Top	100	0	100
	Bottom	100	0	100
BDS	Control	38.35 ± 0.01	2541 ± 123.03	-
	Top	100	0	100
	Bottom	100	0	100