Best Management Practices for

storage of pulses

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Queensland Government

This publication has been compiled by Manoj Nayak, Gregory Daglish, Phillip Burrill and Rajeswaran Jagadeesan of AgriScience Queensland, Department of Agriculture and Fisheries.

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The Postharvest Grain/Commodity Protection Team, working within Queensland Government's Department of Agriculture and Fisheries (DAF) focuses on research, development and extension services for the postharvest protection and quality management of grains, pulses and other processed commodities. The team has strong RD&E capabilities within Australia and across the globe, particularly in stored product pest and resistance management, and the development of new protectants and fumigants. The team also has a track record for capacity building and technology transfer in the Asia pacific region (India, China, Vietnam, Indonesia and the Philippines) and collaborating with other major grain growing continents such as the America and Europe.

Foreword

Advancing Queensland's pulse exports

Pulses are an essential food for millions of people globally. Australia and Queensland are significant exporters of pulses across the globe, with most of the legume crops grown here sold overseas. Nationally, these exports earn an average in excess of $1.99 billion each year, while Queensland's production of chickpeas and mungbeans in 2020–21 was valued at around $264 million.

Australia is known for having among the highest standards in the world for pulse exports. However, maintaining high quality—and therefore optimum prices—is heavily dependent on how pulses are stored. One of the constraints of maximising the quality and value of our pulse production has been the limited knowledge about storing them after harvest.

As part of its vision for Queensland to be a world-leading provider of high-quality, safe and sustainably produced food and fibre, the state government invested $1 million to investigate the knowledge gaps in pulse storage. Collaborating with producers and industry partners, scientists from the Department of Agriculture and Fisheries conducted field trials and laboratory testing, as well as an exhaustive review of published information. The three-year research project identified optimum storage protocols and strategies for managing major pests in stored pulses to help support the state's rapidly expanding chickpea and pulses industry.

This Best Management Practices guide presents Queensland's pulse industry research-based advice for optimising post-harvest storage, including detailed recommendations for hygiene, aeration and fumigation. It is just one of many research outputs that align with our objective to enhance the productivity, profitability and sustainability of value chains through improved practices, innovation and technology. Optimum storage is critical to maximise profitability and sustain Australia's reputation in a highly competitive international market through supply of premium quality, insect-free pulses.

I am proud of the Department's reputation for world-class research, development and extension, and commend the authors on this detailed and practical guide that will inform on-farm storage practices and amplify export opportunities for our producers.

Honourable Mark Furner MP
Minister for Agricultural Industry Development and Fisheries and Minister for Rural Communities

Contents

1 Summary

For safe storage and desirable market quality, pulses should be stored 'cool and dry'. Regular monitoring of storages for both pests and quality is vital.

Hygiene: clean out storages, grain handling equipment and headers well before harvest time to prevent pest and disease carry over from the old residuals. Applying Diatomaceous Earth (DE) in empty storages and equipment will reduce insect pest carry over.

Adopt aeration to promote cool, uniform moisture conditions in storage. This is a key strategy for maintaining pulse quality for export & domestic markets. Ideal temperature regimes for storages are 18–23 °C and 10–18 °C for summer and winter storage seasons respectively.

Fumigation: use gas-tight and sealable silos for phosphine fumigations and follow the registered dose rate of 1.5 g/m^3 (using aluminium phosphide tablets) over a 7–10 day exposure period. This regime will effectively control not only the primary pest, cowpea weevil, *Callosobruchus macculatus* (F) but also other insect pests that infest stored pulses.

Maintain specific moisture content (mc) for each of the stored pulse grains below the specified delivery standard. For example, mc of chickpeas should be below 14% whereas it is less than 12% for mungbeans. Timely harvesting with slightly higher mc can greatly facilitate reduction in the proportion of grain damage and splitting.

2 Background

Grain legumes are generally referred to as ‘pulses’ and are an essential dietary component for millions of people across the globe due to their high protein content and unique flavours.

As well as providing export opportunities, pulses have become an established vital component of sustainable grain production in Australia due to their nitrogen fixation capability in soil, providing nutritional benefits to rotational crops such as cereal and oilseed crops. They also provide agronomic advantages in terms of providing pest and disease breaks to other crops. Nationally, pulses average approximately 10% of the total area planted to crop, but in favourable production areas they can occupy as much as 25% of the total crop area (Australian Grain Note: ‘Pulses’, Australian Export Grains Innovation Centre (aegic.org.au)).

A range of legumes are grown as pulses, except for soybean and peanut that are traditionally seen as oilseed crops. The six major pulse crops grown are chickpea, mungbean, faba/broad bean, field pea, lentil and lupin. In addition, there are some smaller and niche market crops grown including azuki bean, navy bean, cowpea, vetch and pigeon pea. Within these types, the growers have options for numerous varieties, many of which have particular characteristics that suit differing markets.

Chickpeas, faba beans, field peas, lentils, lupins and mungbean combine to produce a 10-year Australian pulse production average of 2.4 million tonnes (Grain Central, 2020, graincentral.com). Most of Australia’s pulses are exported to international markets including Bangladesh, Pakistan, India, Sri Lanka, Korea, Egypt, Saudi Arabia, UAE and Netherlands with annual export earnings exceeding A$1.99 billion (aegic.org.au).

For Queensland, pulses are often grown in rotation with cereal grains, such as wheat, barley and sorghum. The winter pulses include chickpeas, faba beans and field peas, whereas mungbean is the dominant summer crop. As indicated below, mungbeans and chickpeas continue to grow as economically dominant pulses that significantly contributing the State’s economy.

The gross value of production (GVP) for chickpeas for 2020–21 is forecast to be A$135 million, just 2% above the final estimate for 2019–20, but 64% below the average for the past five years (Queensland AgTrends, 2020–21, publications.qld.gov.au). An estimated 221 750 hectares area is sown to chickpeas—43% above the final estimate for 2019–20—due to more favourable autumn planting conditions with boosted soil moisture from much-needed rain. The price is estimated to have fallen around 30% from $765 per tonne (2019–20) to $528 per tonne, due to depressed export market conditions in India as a result of high level of tariff imposed on imports. Alternative export markets, including Bangladesh and Pakistan are being used to divert Queensland chickpeas.

High quality standards of export pulses are one of Australia's key advantage in overseas markets (Source: Deacon Seeds)

The GVP for mungbeans for 2020–21 is forecast to be $129 million—37% above the final estimate for 2019–20 and 36% above the average for the past five years (Queensland AgTrends, 2020–21, publications.qld.gov.au). The area sown to mungbeans is forecast to be 90 000 hectares—30% above the 2019–20 estimate—and is due to increased autumn and winter 2020 rain boosting subsoil moisture levels and the potential for above-average La Niña rainfall in spring. The price is estimated to have fallen since 2019–20 by 7% to $1250 per tonne (for the Premium No 1 grade) but is still historically high.

Australia is well advanced in its knowledge and practices in safe storage of postharvest cereal grains, as most of the research, development and extension over last several decades have been focused on the cereal grains industry. Although pulses are expanding as a major profitable export commodity, the current research information and industry knowledge of best management practices related to postharvest storage is very limited. The safe and effective postharvest storage and handling are critical components in the value chain that aims to maintain Queensland's and Australia's reputation in overseas markets for exporting safe, clean, high-quality food-grade pulses.

This document aims to provide research-based advice to pulse growers and other stakeholders on the best postharvest management practices (including fumigation strategies, aeration cooling and hygiene) for pulses, particularly mungbeans and chickpeas. This advice is based on new research addressing key knowledge gaps as well as information extracted from the scientific literature and other public sources.

3 Market access and quality standards

As pulses are sold for human consumption, quality and export value is directly linked to the visual appearance of pulse seeds. Seed size, good colour, low levels of foreign material and minimal seed damage are some of the receival standards critical to pulse market access and export price.

With many international grain importing countries and consumers increasing their focus on potential chemical residues or other contaminants in grain, it is critical that producers and processors implement pulse industry 'best practice' for storage hygiene and when managing storage insects.

The Australian Pulse Standards is developed through comprehensive consultation among all sectors of the pulse industry, growers, agronomists, researchers, merchants, traders and exporters. This document stipulates standards for heat-damaged, bin-burnt, mouldy, caked or insect-infested pulses, and breaching of any of these can result in the discounting or rejection of product (graintrade.org.au).

The Australian Mungbean Association (mungbean.org.au), also applies a robust quality assurance program throughout its supply chain that underpins its reputation in the international markets. A specific Code of Hygienic Practice for Mungbeans was established in 1989 by the Australian Quarantine and Inspection Services that outlined the growers' responsibilities during storage and handling on farm as well as during transportation to the mill (mungbean.org.au).

Grading losses can be high prior to export if care is not taken with pulse storage and handling.

(Source: OLAM Seeds, Pittsworth, Queensland)

Key defective quality parameters to be aware of

According to the Australian Pulse Standards, definitions for defects apply to the entire seed coat and kernel (graintrade.org.au). A strict principle is applied where a specific quality parameter will only be classified as a defect if its presence exceeds 20% of any one side of the grain.

The following table lists some of the listed defects.

Table 1. **Quality parameters outlined for pulses by Australian Pulse Standards**

Type of defect	Reason
Broken, chipped, loose seed coat and split	Poor harvesting and/or handling techniques, late harvesting may exacerbate this defect
Sappy grain	Grains that have been harvested before maturity and 'soft' when pressed
Intense dark brown to black lesions	Fungal disease
Caked, bin burnt and heat damage	Bacteria or fungi attack in the field or storage, exposure to severe heat during storage due to mould damage or incorrect drying of high moisture grain
Frost damaged, shrivelled and wrinkled	Occurs during maturation phase due to environmental stress such as frost
Sprouted	Wet weather conditions during maturation as well as through moisture ingress during storage
Poor colour	Rapid, premature ripening or through adverse weather conditions and disease during storage
Insect damage	Insects that feed on seed coat and kernel and leave holes and chewing marks

Source: Pulse Standards 2020/2021, graintrade.org.au

4 Harvesting

To attract premium price for pulses, quality must be kept at the highest standard and there are several factors to consider in achieving that. Critical among them is optimum harvest timing and setting up headers correctly.

Here are few points that need careful attention for harvesting pulses:	
• Gentle harvesting will give the best seed quality, so take extra care when harvesting pulses to reduce grain cracking. Rotary harvesters are gentler on the crop and will generally cause less grain damage than conventional harvesters	• Harvesting pulses early at slightly higher moisture content reduces the risk of seed damage and excessive splits during harvest and subsequent handling
• Assess option to 'harvest early' to prevent yield and quality losses caused by pre-harvest weather damage or storms	• Delayed harvesting can significantly reduce the seed quality through weather damage, mould growth and darkening of seed coat
• Aim to harvest before pulse seed mc drop too low (8–10%) to avoid excessive seed damage and splits	• Grain losses from a two-to-four-week harvest delay have ranged from $93 to $238 per hectare, depending on seasonal conditions (grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/the-impact-of-harvest-management-in-chickpeas)
• Store pulse grains safely below the specified delivery standard mc. For chickpeas below 14% and for mungbeans less than 12%	• Prior to harvest, check aeration cooling equipment on storages is in good working order. Providing cool, uniform moisture conditions in storage helps maintain seed colour and limits both mould and storage pest problems

For further details on harvesting, refer to grdc.com.au/resources-and-publications/resources/harvest-resources

5 Storage

The ideal storage for pulses such as chickpeas and mungbeans is a well-designed cone based, sealable silo fitted with aeration fans (storedgrain.com.au/fumigation-guide). Aim to use storages that are easy to clean out when empty and allow for effective use of aeration cooling.

It is critical that silos are checked for pre-existing insect infestations prior to filling with pulses. Several pests can infest stored pulses *(refer to Section 7 for details)* and like cereal grains, pulses are also subjected to the strict market regulation of 'nil tolerance' for live insects. Regular (monthly) monitoring for pests and quality of stored pulses is important *(refer to Section 6)*. Proper hygiene in and around storage structures *(refer to Section 8)* should be carried out prior to and during storage. Pest management through aeration cooling *(refer to Section 9)* and phosphine fumigation *(refer to Section 10)* should be followed once pests are detected.

Always fill silos from the centre roof opening as pulses have high bulk density and loading or out-loading off-centre will put uneven weight on the structure and may lead to its collapse.

Avoid storing lentils in silos with horizontally corrugated walls as the grain can run out from the bottom first and collapse the silo as the grain bulk slides down the silo walls.

As many pulses including chickpeas are susceptible to mechanical damage, the use of conveyor belt is recommended for their handling instead of an auger. If augers are used, care should be taken to minimise the number of times that the pulses are moved. The following points are key to minimise auger damage to pulses:

- Ensure auger is full of grain and operated at slow speed
- Check auger flight clearance – optimum clearance between flight and tube should be half the grain size, to minimise grain lodging and damage
- Operate auger as close as possible to their optimal efficiency, usually an angle of 30 °C

Although silo bags can be used for short term pulse storage (up to three months), they are a less desirable option than silos due to the higher risks of damage to the silo bag membrane. There are several incidents of rejection by marketers of pulses stored in silo bags because of water damage, moulds, taints and odours (pulseaus.com.au/growing-pulses/publications/grain-storage-bags).

If pulses are to be stored in grain bags, all precautions must be taken in terms of site selection, moisture content at filling, bag sealing, monitoring and maintenance.

For all storage types, take extra care to prevent water ingress into storages.

Typical cone-based aerated, sealable silos that are suitable for pulse storage

6 Monitoring grain for pests, quality, and storage conditions

Regular monthly inspections and sampling of storages is essential to check both grain quality and for the presence of storage pests.

Sieve grain samples from the top and bottom of storages and use reference material to correctly identify any pests detected (grdc.com.au/GRDC-BPG-StoredGrainPests). The use of probe or pitfall insect traps located in the grain surface is also helpful for early detections of storage pests.

Including a check on the grain temperature when monthly pest checks are undertaken has several benefits. The operating performance of the aeration cooling system on storages can be assessed to ensure grain temperatures targets are achieved. Pulse storage temperatures of less than 23 °C in the summer/autumn period and less than 15 °C during winter months.

When the ideal low temperature targets (13–15 °C) are achieved in storage it helps preserve both attractive pulse colour and quality attributes such as germination for sprouting mungbeans and viability for pulse planting seed.

In addition, these target temperature regimes significantly reduce storage pest activity and population increases that could quickly result in extensive pulse seed quality damage.

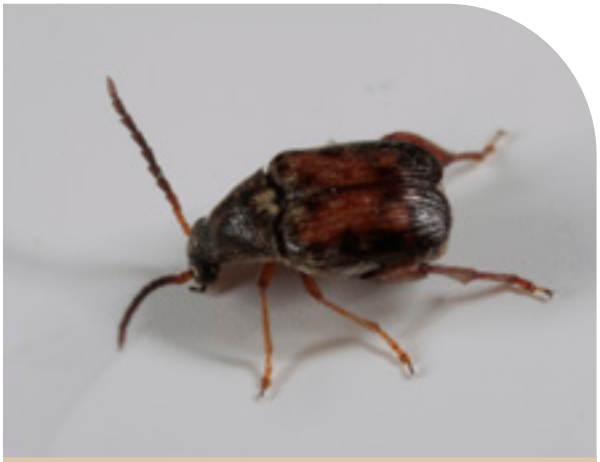
Monitoring equipment critical for successful pulse storage:

- insect sieve
- probe trap
- insect identification information and
- grain temperature probe

7 Storage pests

7.1. Major pests and their identification

Major pests of pulses are put under a group of beetles called bruchids (Family: Chrysomelidae, Subfamily: Bruchinae – formerly Family Bruchidae) that attack fully matured and ripe seeds of legumes and do not attack cereal grains or cereal-based products. Among bruchids, the genus *Callosobruchus* dominates with seven species (*C. analis, C. chinensis, C. maculatus, C. phaseoli, C. rhodesianus, C. subinnotatus* and *C. theobromae*) that are generally called cowpea weevils. The other key pests that are included within the Bruchidae family include bean weevils (*Acanthoscelides obtectus* Say and *A. zeteki* Kingsolver), pea weevils (*Bruchus* spp. and *Bruchidius* spp.), the groundnut bruchid (*Caryedon serratus* Olivier) and the Mexican bean weevil (*Zabrotes subfasciatus* Boheman) (Rees, 2004). In Australia, the cowpea weevil (*C. maculatus* (F.)) is the most prevalent pest of stored mungbean and chickpea (Brier, 2007). Therefore, information on the biology and ecology of *C. maculatus* is presented here covering published as well as new information gathered during our recent research.



Cowpea weevil – Callosobruchus maculatus (F.)

Adult cowpea weevil is orange brown in colour with dark markings and has a distinct globular body (3 mm long), with long legs and long antennae. The bruchids including *C. maculatus*, generally lack the elongated snout of a true weevils that infest cereal grains. The elytra are short and patterned with light and dark patches that do not fully cover the abdomen. Females are slightly larger than males and both are very active and can fly and run rapidly. Although very small in size (0.6 mm), eggs laid on legume seeds are readily visible due to their shiny white colour. Larvae is curved (look like short cream-coloured maggots), feed within the grains and can only be found when an infested grain is slit open; whereas the pupa within a seed can be seen through a translucent window, made by the feeding larva, through which, the adult bruchid emerges (Rees, 2004, Brier, 2007).

In Australia, the cowpea weevil is the most prevalent pest of stored mungbean and chickpea.

7.2. Host range and damage

Callosobruchus maculatus has a wide host range and can attack and successfully reproduce in mungbeans, cowpeas, chickpeas, pigeon peas, field peas, soybeans, and lentils. However, the suitability of different pulses for rapid population growth varies greatly. For example, a recent laboratory study showed that lentil was much less suitable than a range of other pulses including mungbean and chickpea (Bidar et al., 2021). Though the information on host preference is very complex, the general hypothesis is that *C. maculatus* prefers smooth seed coat (testa) over rough ones and not significantly influenced by the colour of the seed. In Australia, *C. maculatus* infestation is often noticed in mungbean and chickpeas (Desi and Kabuli types) and less commonly in any of the other host pulses mentioned above.

Based on the available information, for our research, we have tested the host preference of both laboratory and field populations in five different pulses: mungbean, black gram (urad bean) and pigeon pea (red gram), Desi and Kabuli chickpeas. The experiment was performed after conditioning *C. maculatus* populations in the lab on all the five commodities over five generations. Our results indicated that mungbean was the most preferred diet followed by pigeon pea, chickpea and black gram. Progeny development was very slow in black gram, taking 8 weeks for *C. maculatus* adults to emerge, which was nearly twice the time required in mungbean.

Most of the physical damage to the seed is inflicted through the voracious feeding by *C. maculatus* larvae. The damage is quite visible in an infested seed with a neat circular hole through which the adult emerges, leaving behind a large cavity. Weight loss in cowpea has been estimated to be 5.5% per bruchid (Booker, 1967).

We have assessed the damage potential of *C. maculatus*, using two strains (laboratory established and field collected), in stored mungbeans and chickpeas over a period of 180 days. Three kilograms of each of the commodities were infested with fifty adults of *C. maculatus*. The data on number of live and dead insects, number of infested beans and loss in bean weight over the storage period of one, three and six months were collected. Results revealed that significantly higher number of *C. maculatus* emerged in mungbeans than chickpeas, irrespective of the storage period. For example, approximately 50 000 *C. maculatus* adults had emerged from mungbeans at the sixth month after initial infestation, whereas only 15 000 adults emerged in the case of infested chickpeas. Visual observation showed that every single mungbean has been infested at the end of 6-month storage period. These results clearly demonstrate that bruchid infestation load was three times higher in mungbeans than chickpeas. A similar trend was also observed for percent damage. Mungbeans had an average weight loss of 3.3–16% in the third month and a maximum weight loss of 33% at the sixth month from initial infestation. In chickpeas, *C. maculatus* infestation resulted in maximum weight loss of 3.5% at six months' storage.

7.3. Life cycle

Adult bruchids do not feed on stored produce and are short-lived (up to 12 days under optimum conditions). Female bruchids emit a sex pheromone soon after emergence from pupation that attracts males (Qi and Burkholder, 1982).

During its life, a female can lay up to 115 eggs, although oviposition may be reduced in the presence of previously infested seeds (Parr et al., 1996). The small, oval-shaped translucent eggs are laid by firmly gluing to the surface of the host seed. Seed varieties having smooth seed coat (e.g. mungbean) were found to be more suitable for oviposition than rough-coated varieties (e.g. adzuki beans) (Parr et al., 1998). Another study suggests that the bruchid's ovipositional preference for cowpea seeds with intact seed coats over decorticated seeds (Edde and Amatobi, 2003). The optimum temperature for oviposition was determined to be between 30–35 °C, at which, the egg laying starts within two hours from emergence of the adult female with most eggs laid in the first 24 hours (Credland and Wright, 1989). Eggs hatch within five to six days of oviposition (Howe and Currie, 1964), and upon hatching, the larva bites through the base of the egg, through the testa of the seed and into the cotyledons. The developing larva feeds entirely within a single seed, excavating a chamber as it grows. The frass from the excavation by the larva fills up the eggshell, which makes the egg prominent with white colour. Before pupation, the larva makes a round hole on the surface of the seed while keeping the seed coat intact. This hole looks like a small translucent window, serves as exit point for the emerging adult to push through after the end of pupation, leaving behind a neat circular hole on the seed (Howe and Currie, 1964).

Despite a common perception that *C. maculatus* prefers to attack whole seeds, DAF research shows that the bruchids can successfully breed in split mungbeans. Though the number of progeny produced were relatively lower than the progeny developed in unsplit beans, the adults to progeny multiplication ratio was very high (1:8) even in 100% split beans *(Figure 1, p 12)*. These results clearly indicate that immatures of *C. maculatus* are able to utilise the residual resources such as, graded waste, damaged planting seeds and spills.

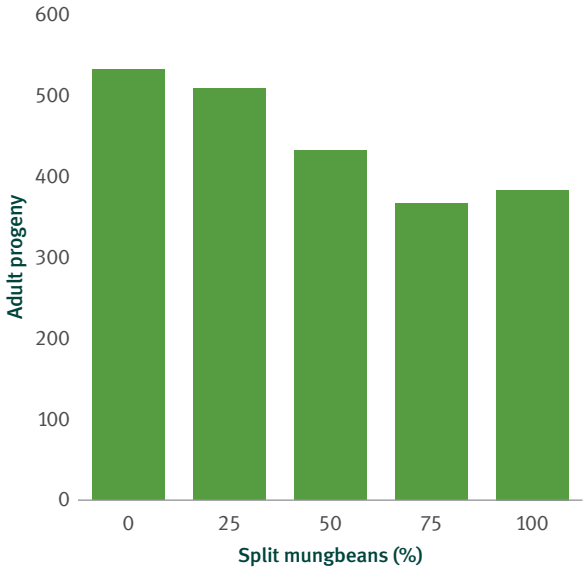
Temperature and relative humidity are key factors that influence development and reproduction of *C. maculatus*, with warm humid conditions favouring population growth (Howe and Currie, 1964). Temperature, in particular, has a major impact. For example, egg–adult development takes about three times longer at 20 °C than 30 °C (Giga and Smith, 1983; Daglish et al., 2021). The type of pulse is also an important factor. For example, mungbeans generally tends to be more suitable than chickpea and a range of other pulses, with faster egg–adult development and higher egg-adult survival on mungbean (Giga and Smith, 1987).

The cowpea weevil's distinctive large white eggs and round exit hole

7.4. Ecology and distribution

Almost all published information on the ecology of *C. maculatus* comes from cowpea research in Africa, but much of this information is likely to be relevant to Australia. Although known as a pest of stored pulses, *C. maculatus* can infest the standing crop and this can lead to infestations in storage (Prevett, 1961; Booker, 1967; Hagstrum, 1985, Zannou at al., 2003). Two estimates of the economic threshold level of field infestation, based on subsequent emergence of adult *C. maculatus*, are 3.3 bruchids per 100 cowpea pods in northern Nigeria (Booker, 1967) and 0.65 bruchids per litre of harvested cowpeas in Florida, USA (Hagstrum, 1985). Although the level of field infestation is likely to depend on multiple factors (e.g. pulse species and variety, and pre-harvest insect management practices), these estimates clearly demonstrate the measurable threat of field infestations that can be carried over to the storage system.

Figure 1: **Reproduction of *Callosobruchus maculatus* (50 adults in 100 g) in mungbeans with various proportions of split mungbeans**



Depending on several factors, including crowding, *C. maculatus* adults can come in an 'active form' or a 'normal form'. Both forms fly but the active form of the population is more likely to disperse and colonise in the field. Investigation of the active form of *C. maculatus* captured in cowpea crops in Benin, western Africa, shows that females undergo a type of reproductive dormancy which ended when flowers and pods appeared (Zannou et al., 2003).

Cowpea weevil is a strong flier and can quickly travel from one infested storage to another

Adult *C. maculatus* are good fliers and the most comprehensive study on flight in this species comes from Nigeria (Taylor and Agbaje, 1974). Males and females were trapped in flight throughout the day and night with small peak in the morning and a larger one in the late afternoon before sunset. About two-thirds of the trapped adults were females of the active form, whereas only about one-third of the adults in nearby infested stored cowpea were females of the active form. In commercial practice, distinguishing between the two forms is impractical, so bruchids detected in storage could be of either form, and assumed to pose a threat to stored pulses.

Callosobruchus maculatus has a worldwide distribution, but most common in warm temperate climatic zones. This pest has been reported as a major pest of stored pulses in USA and Canada, Central and South America, Europe and North Asia, Mediterranean basin, Africa, South and South East Asia, Australia and Oceania (Rees, 2004). Genetics suggest an African origin for *C. maculatus*, with an ancient expansion into Asia, followed by more recent introductions to other parts of the world, facilitated by trade in cowpea and other pulses (Kébé et al., 2017). In Australia, the infestations of this pest in stored mungbeans have been more frequently reported from central and southern Queensland, although it has been reported occasionally from northern NSW (Brier, 2007). Given the successful spread of *C. maculatus* globally, with the help of trade and other human activities, we can expect any geographic expansion in Australia of the production of pulses that are prone to attack by *C. maculatus* to be accompanied by an expansion of the distribution of this species.

7.5. Other pests that may attack stored pulses

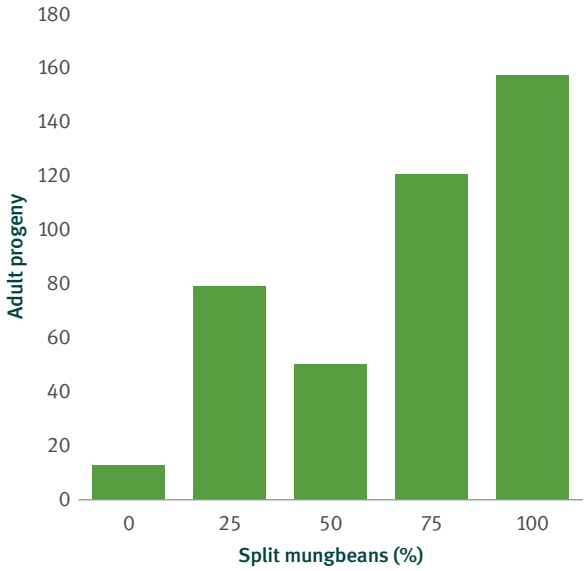
Although bruchids are considered major pests of pulses, other stored grain pests that infest cereals in Australia have also been reported for attacking stored pulses. These include the lesser grain borer, *Rhyzopertha dominica* (F.), red flour beetle, *Tribolium castaneum* (Herbst), saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.) and weevils Sitophilus spp. (Giles, 1977). Recently, several beetle pests of cereals have been detected in mungbean and chickpea samples collected from storages in Queensland. For example, we have collected 28 chickpea samples from farms across Queensland between July 2019 and May 2021. Of these, 24 samples had no *C. maculatus* but had major cereal pests including *R. dominica, T. castaneum, S. oryzae, O. surinamensis* and *Sitophilus* spp. There were three samples infested with three of these pest species and an additional three samples had four of them. Similarly, of the nine mungbean samples collected over this period, six had *C. maculatus* along with one or two cereal pest species. All three mungbean samples clear from *C. maculatus* had at least one cereal pest infestation. These results suggest that cross infestation of pulses by the insect pests that attack cereal grains is very common. This could be because stored product insects are highly adapted to multiple resources and environments, or simply associated with storing pulses in silos that had previously contained infested cereal grains.

To further investigate this aspect, we tested the infestation potential of two major cereal pests, *T. castaneum* and *R. dominica* in two conditions:

1. Mungbeans damaged from prior infestation of *C. maculatus*
2. Mungbeans containing different proportions of split beans, ranging from no splits to 100% splits

Our results showed that both the pests preferred to infest and multiply in bruchid damaged mungbeans over split or unsplit beans. Though *R. dominica* managed to breed well in split mungbeans, with the number of progeny positively correlated with the percentage of splits beans *(Figure 2)*, very few progeny of *T. castaneum* emerged from either split or unsplit mungbeans. These results show that infestation of both cereal pests can occur in stored pulses and be problematic in the case that the storage either contained prior bruchid infestation or split mungbeans. Although neither *T. castaneum* nor *R. dominica* necessarily cause serious physical loss, the presence of these pests will jeopardise the insect-free status of pulses.

Figure 2: **Reproduction of *Rhyzopertha dominica* in mungbeans (50 adults in 100 g) with various amounts of split mungbeans**



Rust-red flour beetle – Tribolium castaneum (Herbst)

Lesser grain borer – Rhyzopertha dominica (F.)

8 Hygiene

It is important to remember that insects need only a small amount of grain to survive and reproduce to become thousands in numbers and can walk and fly to spread and infest other grain storages.

Therefore, hygiene, involving physically cleaning of empty silos and grain handling equipment prior to filling with newly harvested pulses is a critical step in reducing insect pest carry over and contamination. Removing spilt and leftover grain helps in removing the feed source and harbour sites for insect pests.

Hygiene implementation checklist

- ☑ Empty silos and grain storages
- ☑ Aeration ducts
- ☑ Augers and conveyers
- ☑ Harvesters
- ☑ Field and chaser bins
- ☑ Spilt grain around grain storages
- ☑ Leftover bags of grain or gradings
- ☑ Carry-over planting seed and stockfeed

Clean down empty storages with either a water wash-out followed by a few days of drying or use air pressure and long handled brooms. Vacuuming and fire-fighting hoses can also be utilised for improving results.

As pulses are used for human consumption it is important to ensure rodents, birds, other wildlife and domestic animals are excluded from gaining access to storages. Storing chickpeas in open grain sheds is an example where extra precautions are required.

Currently, no spray-on chemical treatments are registered for applying to stored pulses. Therefore, most common insecticides used for storage surface treatments are off limits for pulse storage. When unregistered chemical residues are detected by grain buyers, there are serious long-term consequences for domestic and export markets.

Inert dust or Diatomaceous Earth (DE) (amorphous silica) is a naturally occurring mined product with insecticidal properties. It holds excellent oil and water absorption characteristics and therefore has been used as a structural treatment insecticide in pest management including grain storage. In Australia, DE is applied inside empty concrete and steel silos, metal bins, grain sheds and headers as a hygiene treatment.

DE can be applied as a dust or slurry spray onto internal surfaces of storages and equipment. Once old grain residues have been physically removed or washed out, DE is then applied as a non-chemical treatment to reduce insect pest carry over. Before treating storage structures with DE, it is important that growers consult with potential buyers, as some markets may have restrictions on traces of DE on pulses.

Though some information on the structural efficacy data for DE is available for cereal grain pests, no published information was available in relation to pests of pulses. Further, very limited information is available in relation to the efficacy of DE at higher temperatures (›25 °C).

Applying a Diatomaceous Earth (DE) treatment to internal storage surfaces controls any remaining storage pest insects following the physical clean-up (Source: GRDC)

Considering this, DAF has evaluated the efficacy of DE against *C. maculatus* on two of the most used surfaces in storage structures (concrete and steel) over a period of 0 to 3 months. The required amount of DE, representing the standard dust application rate 2 g/m², was applied to mini-bioassay blocks made of concrete or steel. Some blocks were used immediately for testing and others were stored for three months before being tested. The 0- and 3-month tests were initiated by confining *C. maculatus* adults on the bioassay blocks and assessing subsequent mortality. The bioassays were also conducted at 25 °C and 55% relative humidity (RH) and 30 °C and 70% RH.

Our results revealed that the standard dust application rate of DE (2 g/m²) was very effective against *C. maculatus* adults at 25 °C and 55% RH. Complete mortality of adults of *C. maculatus* was observed within two days after the application of DE, in both steel and concrete surfaces, zero months after treatment. Though similar results were observed at three months after treatment, some adults survived at day seven in both treated structures, indicating efficacy of DE declining over time. DE was not effective at 30 °C and 70% RH in either steel or concrete surfaces. For example, at zero month, complete mortality had not been achieved in either steel or concrete.

Overall results from this study confirmed that the current application rate of DE is effective against *C. maculatus* in both steel and concrete storage structures at 25 °C. However, its use in warm and humid conditions needs to be investigated with potential new DE formulations in the future.

For more information see the GRDC fact sheet: grdc.com.au/GRDC-FS-HygieneStructuralTreatments.

9 Aeration

9.1. Overview

Population growth of insects is strongly dependent on temperature. The temperature of mungbean and other pulses at the start of storage will reflect the temperature at time of harvest. Harvest temperatures around 25 to 30 °C or greater are possible and these are favourable to insect population growth. The dependence of insects on warm temperatures also provides the possibility of using aeration cooling to manage insects in stored pulses.

The aim of aeration cooling is to push ambient air through the grain bulk to reduce temperature to a level that limits insect population growth. A well-managed aeration system can reduce the grain harvest temperatures by at least 10 °C, which has significant impact on reducing insect-pest problems and ensuring maintenance of grain quality in storage. Aeration does not eliminate an existing infestation, instead it slows down the development and multiplication rate of storage pests. Therefore, the most optimal use of aeration is as part of an integrated pest management strategy. Overall, as a non-chemical method, aeration-cooling offers the following advantages for pulse storage:

- Creates uniform moisture conditions throughout the grain bulk
- Prevents moisture migration
- Maintains seed viability (germination and vigour)
- Reduces mould growth
- Lengthens or stops insect reproduction cycles
- Slows seedcoat colour darkening and market quality loss

The Australian Pulse Standards PULSES (graintrade.org.au) set a maximum moisture receival limit for each pulse grain to ensure safe storage. Care is required to store pulses below these specified limits to prevent self-heating, mould development and grain quality damage.

Grain is an effective insulator and holds many tiny pockets of air within a stack, and without aeration, it will maintain its warm harvest temperature for a long time during storage. The grain at the top of a silo is particularly susceptible to damage without aeration cooling. During daytime, the sun heats up the silo roof and internal head space air making the surface of the grain warm *(refer to diagram p 17)*. The top of the silo, however, cools down with sunset and the warm, humid air inside the silo head space then condenses on the cool roof and walls, generating moisture on the surface grain. Damp grain is vulnerable for mould and insect growth. To avoid these fluctuations, it is advantageous for growers to fit silos with aeration system to provide a cool, optimal storage environment for the grain.

Cooling or drying: *making the right choice*

Aeration systems are designed to carry out either a drying or cooling function, not both. Managing the aeration system is critical and it is different for cooling or drying, with fan run times required at different times of day and at different intervals. An automatic aeration controller provides a significant advantage as it constantly checks ambient air temperatures and humidity to select the best times to run fans for either cooling or drying functions. This is more reliable than trying to manually turn fans on and off at appropriate ambient conditions.

For cooling, an airflow rates of 2–4 litres per second per tonne (L/s/t) is required. Aeration drying is reliably achieved with fans delivering 15–25 L/s/t, typically powered by significant larger performance fans.

The fans selected in aeration systems needs to be selected for the size of the silo, type of grain stored, and the function required, cooling or drying. For example, low-capacity fans cannot push a drying front through the grain bulk fast enough to safely dry grain through the whole grain depth. On the other hand, using high-capacity fans for cooling risks increasing grain moisture very quickly if fans are running when ambient conditions are close to the 85% RH.

9.2. Cooling

Although cooling can be achieved with relatively low airflow rates, it is important to have appropriate ducting location and design to achieve uniform distribution of air through the grain stack.

For most storage facilities we recommend using a good quality automatic aeration controller with a sensor measuring both ambient air temperature and humidity to automatically turn on fans at optimum times to cool grain.

Manual operation of aeration cooling fans

There are three stages when operating aeration cooling fans from the start of harvest:

1 When grain covers the ducting, turn on aeration fans while filling silo. Run continuously (24 hrs/day) until the first cooling front comes through the full grain depth. This usually takes 3–5 days

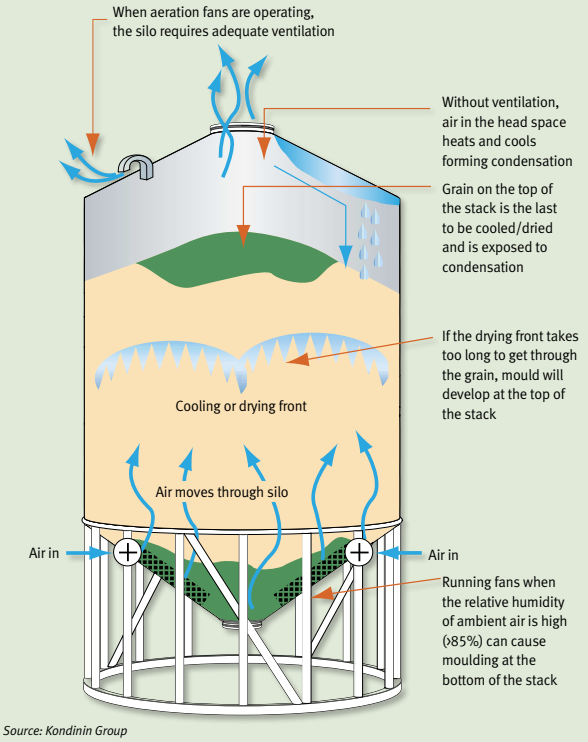
2 Next, run fans for approximately 9–12 hours per day for the next 5–7 days. Select the cooler night air but avoid extended periods of high humidity air which may wet grain. Avoid fog, misty or showery conditions

3 This is the final longer term 'protect' phase. In summer, grain temperature should be close to 20 °C. In winter months grain should be below 15 °C. Operate fan for approximately 100 hours per month, selecting cool, mostly dry air from 3–5 days per week to maintain cool grain conditions. An automatic controller will be significantly more reliable at this task

Automatic controllers are available that will automatically step through the three stages outlined above.

Critical steps for deciding cooling or drying

- Pulses dry enough to meet receival specifications for sale (12–14% mc) can be cooled, without drying to maintain quality during storage
- Pulses with high moisture (>14%) require drying to reduce the moisture content to the desired level and then cooling to maintain quality during storage
- When drying is not available at harvest time for over-moisture grain, moist grain can be safely held temporarily when continuously aeration cooled. Monitor grain daily during this time. Dry grain promptly when equipment is available to prevent grain damage in storage



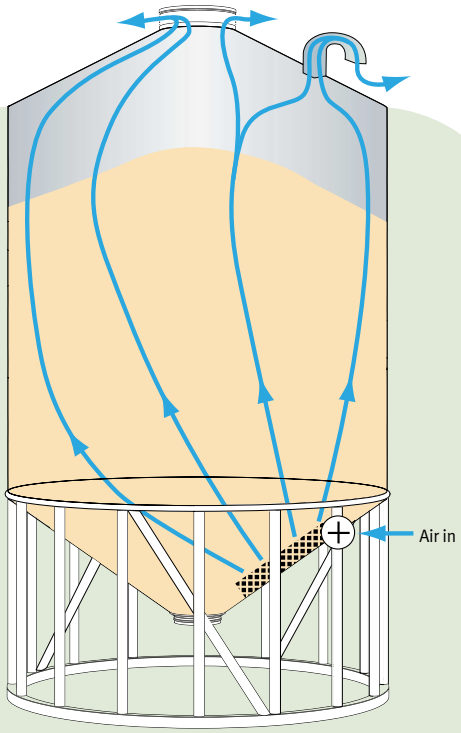
Source: Kondinin Group

For more information refer to **storedgrain.com.au/aeration-cooling**.

Aeration cooling is critical for pest control and maintenance of grain quality (source: GRDC)

Maintaining and checking aeration equipment

- Check grain temperatures to see if you are achieving the target temperatures of 18–23 °C during summer storage and less than 15 °C during the winter period
- When checking silos each month for insects, also look at the meter on the aeration auto controller to make sure fans are averaging around 100 hours per month (+/- 20 hrs)
- Once per year use a good quality thermometer and relative humidity reader to check the aeration auto controller's sensor has not been damaged and is readings correctly
- Manually test-run fans on silos to check they are all operating, clean fan impellers of built-up dust if required



Key components for Aeration systems:

- correct size fans
- internal ducts
- roof vents
- auto fan controller

Aeration fan selected for cooling airflows outputs of 2–4 L/s/t

Example of an automatic aeration fan controller used to select optimum ambient temperature and humidity parameters for storage aeration fans

There is considerable published information on the impact of temperature on population growth of major pests of stored cereals that is relevant to an aeration cooling (e.g. Birch, 1953; White 1988). Although there are published studies on temperature-dependent development and reproduction of *C. maculatus*, most have not provided data enabling identification of a target temperature for aeration cooling. Giga and Smith (1983), for example, showed that population growth of *C. maculatus* on cowpea was greatly reduced at lower temperature, but population growth was still possible at 20 °C which was the lowest temperature tested. Therefore, a laboratory study was completed to enable the accurate estimation of a target temperature for aeration cooling in this species.

Bruchid population growth was determined in mungbeans at 15, 17.5, 20, 22.5, 25, 27.5, 30, 32.5 and 35 °C (all at 60% RH). Two field collected populations were tested: a long-established laboratory strain, and another that had been in culture for only 1–2 years. The results for the two strains were similar, so only the results for the recently collected strain are discussed. Population growth occurred over a wide temperature range and was strongly temperature dependent. Generation time tended to decrease with increasing temperature *(Figure 3)*. Multiplication rate, or the number of adult progeny produced per parent, tended to increase with increasing temperature *(Figure 4)*. These results show that maximum population growth would occur at 30–35 °C.

The estimated target temperature for aeration cooling was 17 °C. There may be situations where aeration cooling to 17 °C is not possible, because of the prevailing local climatic conditions. Cooling to as low as 20 °C, however, will reduce population growth significantly, resulting in less damage and fewer bruchids needing to be controlled using phosphine fumigation prior to sale.

Figure 3: **Effect of temperature on generation time of *Callosobruchus maculatus* on mungbean**

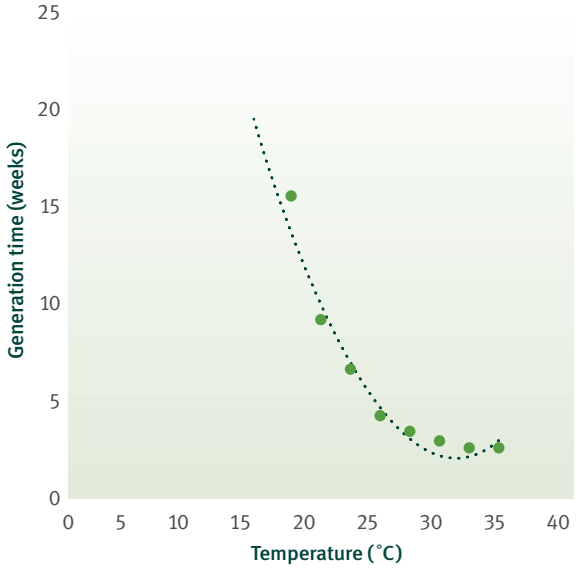
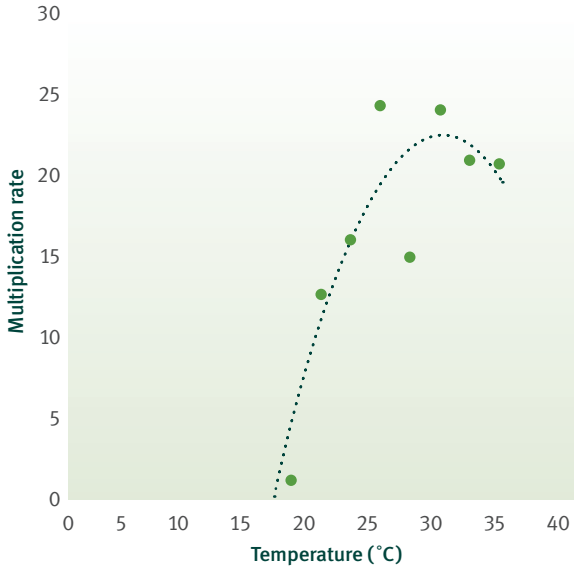


Figure 4: **Effect of temperature on multiplication rate of *Callosobruchus maculatus* on mungbean**



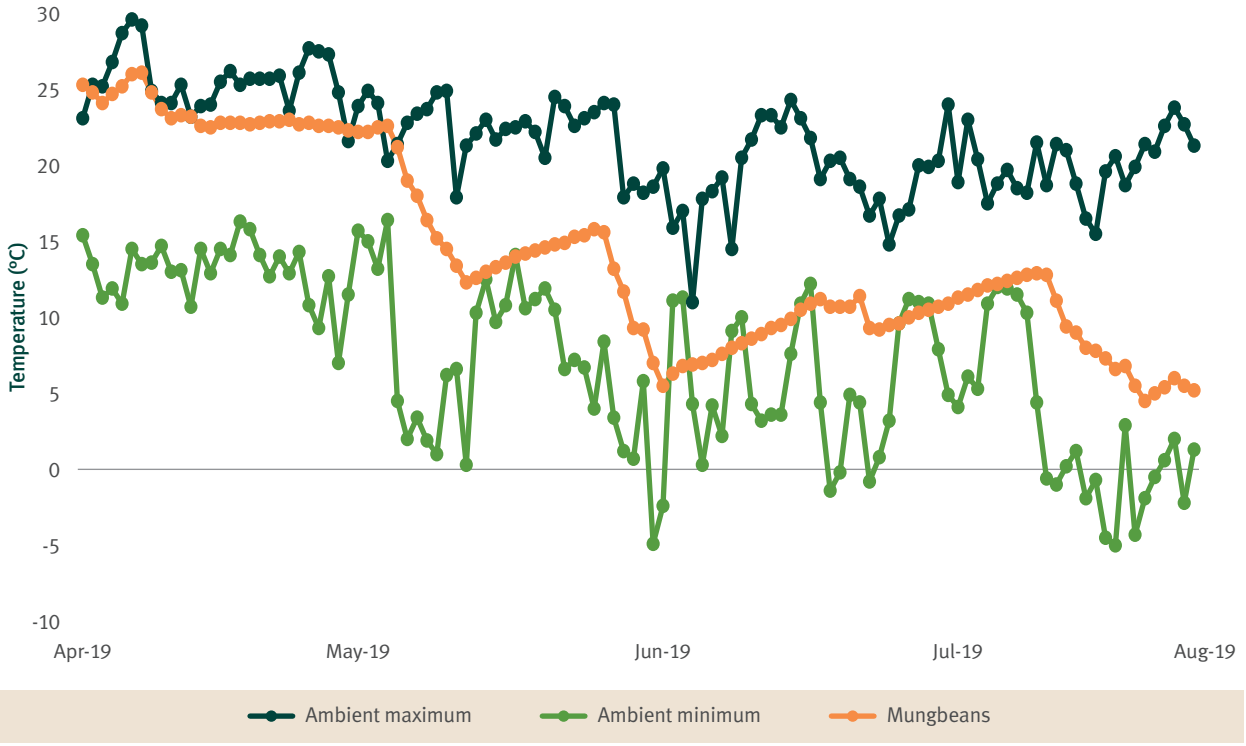
A field trial was conducted from April to July 2019 (16 weeks duration) at the Hermitage Research Facility, Warwick, to determine the feasibility of using aeration cooling in mungbeans. Mungbeans (Jade variety) were stored in a silo (8 t capacity) fitted with an aeration fan and an automatic aeration controller (Grain Safe 5000 Aeration Controller, Control Unlimited, Toowoomba, QLD, Australia). The fan airflow rate was adjusted to 7 L/s/t and the aeration controller was set to automatic function. The automatic controller is designed to cool grain while avoiding moistening the grain. Thus, the aeration fan does not run continuously but according to software decisions made by the controller based on half-hourly monitoring of the ambient temperature and humidity. The controller switched off fans if relative humidity reached 85%.

Temperature and relative humidity sensors (OPI, Calgary, Alberta, Canada, advancedgrainmanagement.com) recorded conditions at three locations inside the mungbean bulk. These sensors were placed near the top, middle and bottom of the mungbean bulk. Daily ambient maximum and minimum temperatures were sourced from Bureau of Meteorology (bom.gov.au).

Temperature inside the mungbean mass was about 25 °C at the beginning of the 16-week trial and about 5 °C at the end *(Figure 5 p 20)*. The target temperature for aeration cooling from the laboratory study was 17 °C and the temperature at all three sensor locations was less than 17 °C from about five weeks onwards. To achieve this result, the fan was operating for about 24% of the time—68% of the time during the first week, 50% of the time during the next week, and 19% of the time during the remainder of the trial. When the target temperature was achieved within the mungbean mass, a set of test insect cages containing all the life-stages of *C. maculatus* were buried within the beans at the top of the silo (30–100 cm depth) in an effort to evaluate the effectiveness of aeration in reducing the rate of development of all the life stages. Our results clearly indicated that maintaining the target temperature 17 °C or below over 4–6 weeks was detrimental to larvae, pupae and adults. Though some proportion of eggs survived this regime, progeny numbers emerged from grains at 17 °C was remarkably lower than the numbers emerged in grains stored at normal culturing regime at 30 °C and 55% RH.

This trial shows the potential for using aeration cooling in mungbeans to prevent or slow population growth of *C. maculatus*. Warwick typically has cool autumns and winters as reflected by the very low temperatures that were achieved during this trial. However, many other districts, where mungbeans or other pulses are stored, can have temperatures below 20 °C during the cooler months, indicating the potential for using aeration cooling more widely.

Figure 5: **Aeration cooling of a silo containing mungbeans from April to July 2019 at Warwick. The temperature presented in the mungbeans is the average of that recorded at three locations within the bulk**



9.3. Drying

Aeration drying can use the ambient air to dry the grain. Drying involves pumping air through the grain bulk at high flow rates at a temperature and humidity that will enable the removal of excess moisture from the grain. It requires a specifically designed system and is a much slower process than aeration cooling. Pulses with higher mc will require drying or blending to maintain the desired quality in storage. Aeration drying requires operation with long run times each day and at a much higher airflow rates with fans delivering 15–25 L/s/t.

Using an automatic aeration controller with aeration drying functions included in the software is recommended for reliably selecting the appropriate ambient air conditions suited to safe grain drying.

Blending dry grain with higher moisture grain may also be a suitable alternative.

10 Phosphine fumigation

10.1. Overview on good fumigation practices

Phosphine is predominantly used in Australia and across the globe to disinfest grain and other stored commodities. A nationwide survey in 2010 showed that 85% of the growers in Australia use phosphine to disinfest their grain stored on-farm (Fumigating with phosphine, other fumigants and controlled atmospheres: Do it right, do it once – A Grains Industry Guide (storedgrain.com.au/fumigating-with-phosphine-and-ca/). In the absence of viable affordable alternatives applicable across a range of storage structures and international acceptance as a residue-free treatment, phosphine is expected to be relied upon by the industry for the foreseeable future.

Pivotal to achieving the best outcome from a phosphine fumigation is the gas-tightness of the storage structure during a fumigation. A gas-tight storage ensures that there is sufficient phosphine gas concentration for long enough time to effectively control all life stages (egg, larva, pupa, and adult) of the target pest.

As silos are the most common type of on-farm grain storage in Australia (approximate 82% of all storage facilities nationally), growers are advised to follow Australian Standard (AS2628) to undertake a five-minute, half-life pressure test to ensure the gas-tightness of silos, both at the time of silo installation as well as prior to each fumigation. (storedgrain.com.au/fumigation-guide).

Although phosphine is available in several commercial forms, the preference for on-farm use is solid aluminium phosphide formulations (tablets, bag chains and blankets). These solid forms react with moisture in the air to release phosphine gas. While bag chains are considered as the safest to handle, tablets are generally used for smaller silos, whereas phosphine blankets are designed for bulk storages larger than 600 tonnes.

Irrespective of the amount of grain stored, the application rate of aluminium phosphide (1.5 g/m³) in an airtight silo remains the same and is based on volume. Longer exposure periods are recommended at low grain temperatures. Fumigation is **not** advised for grain temperatures below 15 °C (https://nufarm.com/au/product/fumitoxin/)*. Higher concentration and exposure periods are also recommended for control of a range of phosphine resistant pests.

**Product used as an example only. This is not an endorsement.*

Conduct a silo pressure test prior to fumigation to ensure a gas-tight fumigation for successful storage pest control.

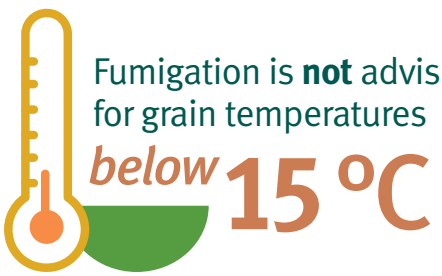
Phosphine fumigation using the tablet in trays place in the silo headspace

Ground level application box for applying phosphine tablets including fumigation recirculation plumbing using the fan for rapid gas distribution in larger silos (greater than 150 t capacity)

The current application rate for phosphine tablets is 1.5 tablets per cubic metre for 7–10 days, depending on grain temperature. Read label instructions carefully. This dose equates to two tablets (2 g of phosphine) per tonne of storage capacity. A properly maintained gas-tight, sealable silo should maintain at least 360 ppm of gas over 7–10 days (**https://nufarm.com/au/product/fumitoxin/**).

Once removed from its sealed container, phosphine gas evolves from the tablets in presence of moisture in the air, hence it is recommended that when applied, the tablets are spread evenly across a large tray before hanging them in the head space of a silo.

Some silos are fitted with a purpose-built facility to apply phosphine from the base of the silo. This has an added safety advantage as the operator doesn't need to apply phosphine from the top of the silo. This application method must have a passive or active (fan driven) air circulation system to carry the phosphine gas out of the confined space as it evolves, to facilitate the dispersal through the stored grain. Without air movement, phosphine can reach explosive levels if the gas from the tablets is left to evolve in a confined space.



After the recommended fumigation period stated on the label, the silo is ventilated over 1–5 days depending on the availability of an aeration fan with the silo that expedites the ventilation.

Ventilation should be followed by a two day withholding period, making the complete phosphine fumigation process typically around 13–17 days prior to grain delivery (**https://nufarm.com/au/product/fumitoxin/**).

Due to the highly toxic nature of phosphine, recommended safety precautions as stated on the label should be followed. These include the use of cotton overalls buttoned to the neck and wrist, eye protection, elbow-length PVC gloves and breathing respirator specified for use with phosphine gas.

A warning sign reading 'DANGER – POISONOUS GAS, KEEP AWAY' must be placed on the silo to inform others to stay away from a silo under fumigation (storedgrain.com.au/fumigation-guide).

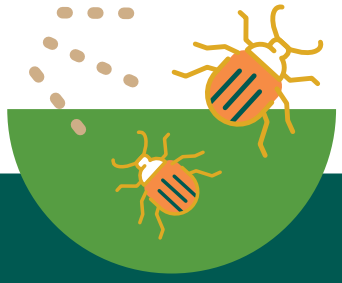
The current phosphine label for tablets has dried pulses in its list of commodities for fumigation. As most of the research and development involving phosphine has been focused on storage pests of cereals over several decades, there has been a serious knowledge gap on its efficacy against major pulse pests such as *C. maculatus*. To address this, our research team has undertaken a series of laboratory and field validation experiments to establish practical phosphine fumigation protocols to manage *C. maculatus* in stored pulses including mungbeans and the Desi and Kabuli types of chickpeas.

10.2. Laboratory established fumigation data on mungbeans and chickpeas

A comprehensive laboratory study was undertaken involving two *C. maculatus* populations that were collected from infested mungbeans stored in Queensland (Kingaroy and Toowoomba), and had been cultured in organic mungbeans in the laboratory at 30 °C and 60% RH. Fumigations were conducted on mungbean and two types of chickpeas (Desi and Kabuli).

Test insect populations were cultured in organic mungbeans and chickpeas as described previously by Daglish et al., 2021. Before the fumigation assays, it was ensured the experimental jars contained infested mungbeans and chickpeas representing all insect life stages (eggs, larvae, pupae and adults) of *C. maculatus*. These mixed age population samples were subjected to different phosphine concentrations and exposure periods at 25 °C.

Phosphine gas was generated from aluminium phosphide tablets and measured on a gas chromatograph. This known concentration of the source gas was used to achieve the target concentrations of 0.5 (360 ppm) and 1.0 mg L^{-1} (720 ppm) for this study. Each concentration was evaluated over two or more exposure periods of up to 7-days. The two fumigation regimes are aimed at covering both forms of phosphine (tablet and cylinderised) currently used in Australia.



Our laboratory studies reconfirmed that *C. maculatus* adults are the most susceptible life stage to phosphine, while the eggs and other immature stages are the most tolerant stage.

Experimental jars containing mixed-age populations of *C. maculatus* were placed inside air-tight glass desiccators mimicking mini-silos, into which the required volume of phosphine gas for each selected concentration was injected. Each experiment was replicated twice, and parallel untreated control experiments with normal atmospheric air were run for comparison. After fumigation, the experimental jars containing both treated and untreated insects were moved to a recovery room and maintained under controlled environment of 30 °C and 60% RH for further observations.

Two efficacy assessments were undertaken to cover all life stages of *C. maculatus* test populations. The initial assessment was taken seven days post-fumigation to determine mortality rates of adults sieved from the fumigated mungbeans or chickpeas. A second assessment was undertaken six weeks post-fumigation to measure the impact of the fumigation on eggs, larvae or pupae present during the fumigation.

Although the two tested populations varied in tolerance to phosphine, there was some consistency in that, irrespective of the two concentrations tested (0.5 and 1 mg L^{-1}), a three or four day fumigation period was not effective in controlling immature life-stages in either mungbeans or chickpeas. On mungbeans, both 0.5 and 1 mg L^{-1} over a seven day fumigation were found adequate to achieve complete control of all life stages of *C. maculatus*. On Kabuli chickpeas, a seven day exposure of 0.5 mg L^{-1} (360 ppm) was required to achieve complete control, whereas on Desi chickpeas, the same result was achieved over a four day exposure period. Our results show that a seven day fumigation at 0.5 mg L^{-1} (360 ppm) is sufficient to achieve complete control of all life stages of *C. maculatus* at 25 °C in both the commodities.

Our laboratory studies reconfirmed that *C. maculatus* adults are the most susceptible life stage to phosphine, while the eggs and other immature stages are the most tolerant stage. The high level of susceptibility of adults, together with their short lifespan, has important practical implications. In mungbeans, for example, fumigation for three days at the lowest test concentration of 0.5 mg L^{-1} (360 ppm) caused nearly complete adult mortality but subsequently allowed the emergence of many adult progeny. These results suggest that an insufficient fumigation could appear successful, based on the presence of many dead adults, despite there being many immatures hidden inside the mungbean seeds which withstand the low concentrations of phosphine and complete the lifecycle with freshly emerged adults reinfesting. Thus, repeated poor fumigations that kill adults but not immatures will trigger the development of genetic resistance eventually.

10.3. Field validation of phosphine fumigation

We conducted two silo-scale trials at the Hermitage Research Facility, Warwick, to assess phosphine efficacy against *C. maculatus* in mungbeans and chickpeas stored under field conditions.

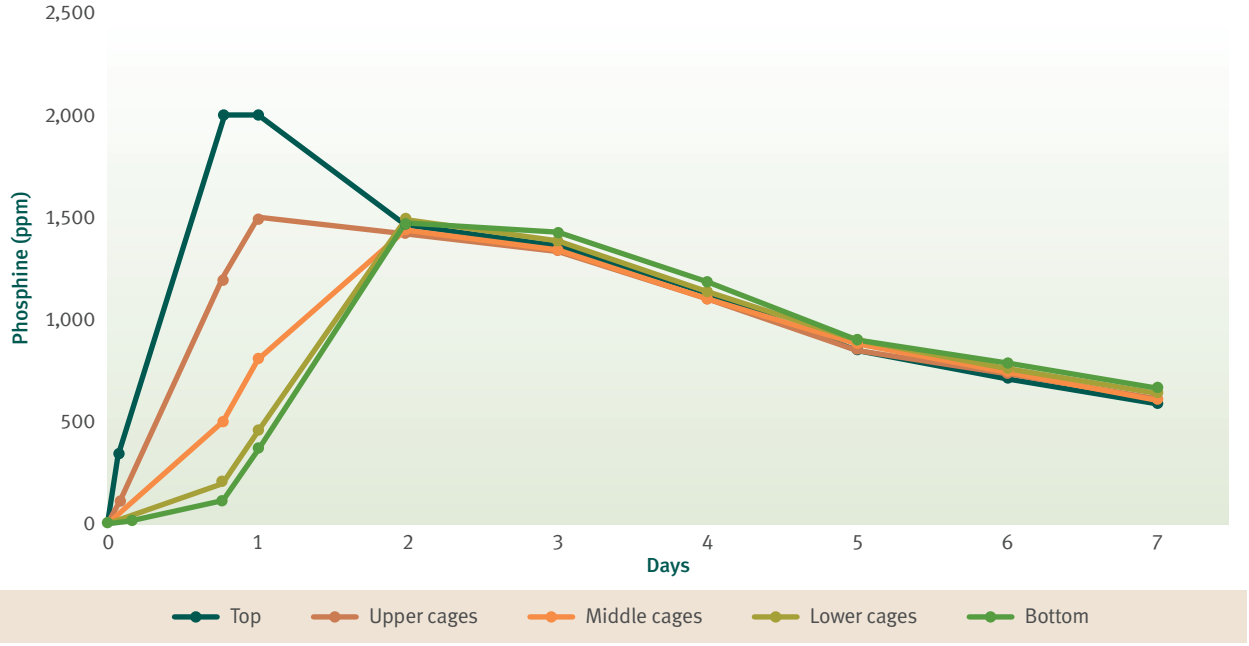
The mungbean trial was initiated in March 2019 using recently harvested mungbeans (Jade variety) stored with a temperature of 29 °C and mc of 10%. The chickpea trial was undertaken in March 2021 using recently harvested Desi chickpeas (PBA Hat Trick variety) with a temperature of 26 °C and mc of 11.4%.

In each trial, two 11.1 m^3 (8 t capacity) sealable silos were used, one marked for phosphine fumigation and the other used for untreated control. The silos had a conical top and conical bottom and was 3.7 m high and 2.2 m wide and were almost full of mungbeans or chickpeas. The silo designated for fumigation was checked following the standard half-life pressure test and was found to be gas tight. Mixed-age populations of reference *C. maculatus* populations reared in the laboratory on either mungbeans or chickpeas, were placed in insect cages and were inserted into the mungbeans or chickpeas inside the silo. Sets of cages were located just under the surface of the mungbeans or chickpeas and near the bottom of the silo and were termed 'top' and 'bottom' cages. Other sets of cages were located about one-third, one-half and two-thirds of the way down the silo, and were termed 'upper', 'middle' and 'lower' cages. In total, two reference *C. maculatus* populations were used for the mungbean trial whereas three reference populations used for the chickpea trial. Three batches of each pest population were placed at different levels of the silo prior to fumigation. Three batches of control cages, representing each of the reference population were inserted into the mungbeans or chickpeas in the second silo that was not fumigated with phosphine.

Aluminum phosphine tablets were placed on the top surface of the mungbeans inside the silo to be fumigated, following the current label rate of 1.5 tablets per cubic metre of empty silo volume, which is equivalent to 1.5 g/m^3 of phosphine gas. Phosphine concentrations were measured at the upper, middle and lower cage locations 1–2 times per day during the seven day fumigation, using a Canary Silo-Check® monitor. Stainless steel tubes had been inserted into the centre of mungbeans prior to fumigation, and nylon tubing led from the steel tubes to ground level where the readings could be taken.

All insect cages were retrieved from the silos after a one-day (24 hour) gas venting period at the end of the seven day fumigation period and were taken to the DAF laboratories at the Ecosciences Precinct for efficacy assessments. The efficacy assessments were similar to those described for the laboratory fumigation study *(see Section 10.2)*.

Figure 6: **Phosphine concentrations (ppm) measured inside a silo containing mungbeans fumigated in March 2019 at the current label rate of 1.5 tablets/m^3 of silo volume for 7 days**



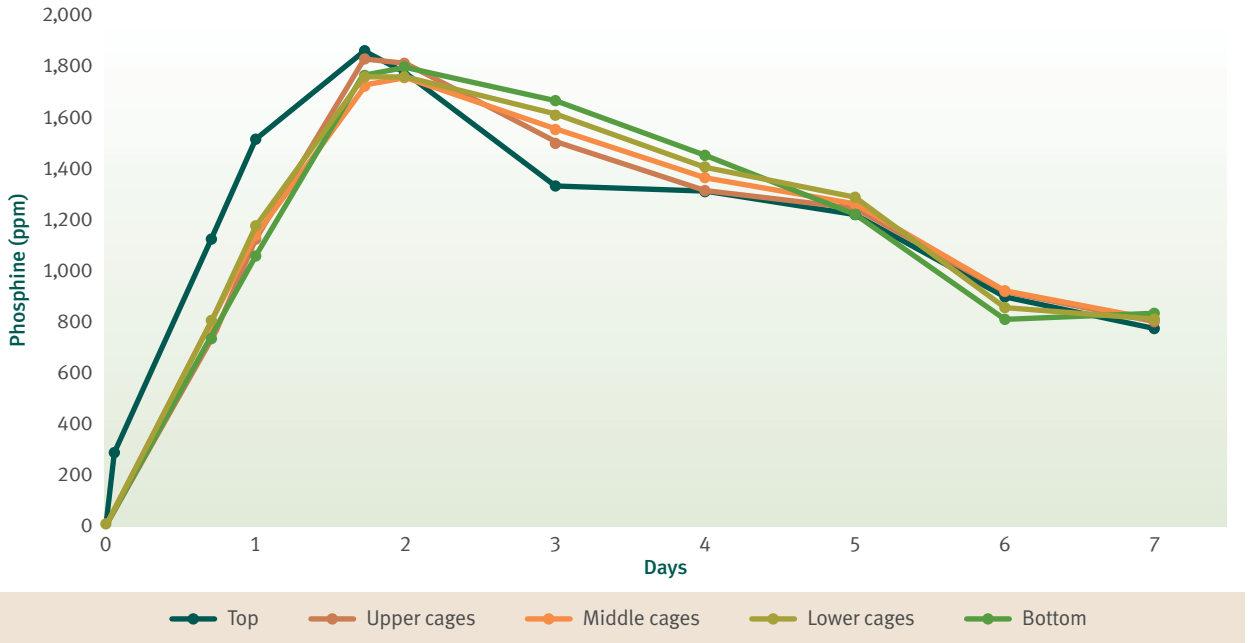
As shown in *Figure 6*, phosphine concentrations initially rose quickly across various locations within the mungbean filled silo, as the gas was liberated from the aluminium phosphide tablets. Levels then peaked and then slowly declined. The two likely reasons for the concentration decline are leakage of small volumes of phosphine through the pressure relief valves, and phosphine sorption by the mungbeans. After peaking to ›1400 ppm (›1.9 mg L^{-1}), after two days, phosphine gas was uniformly distributed through the mungbeans and remained so for the rest of the fumigation period. Despite declining levels over time, phosphine concentration remained above 600 ppm for a significant duration (five days). There was complete control of adults and immature stages of both test populations as revealed from the post-fumigation assessments.

For the chickpea trial *(Figure 7)*, phosphine concentration peaked to ›1,000 ppm (›1.4 mg L^{-1}) at all sampling points in the silo within the first day of fumigation, and concentration remained › 700 ppm (›1.0 mg L^{-1}) at all sampling points for the remaining six days. The cages containing mixed-age colonies of three reference pest populations were retrieved from the silo post fumigation and assessed in the laboratory for surviving adults and emergence of immatures. There was complete control of all life stages of all three *C. maculatus* populations, confirming the success of the fumigation.

To validate the effectiveness of the laboratory established phosphine fumigation protocol, mixed-age colonies of 14 populations of *C. maculatus* collected from various farm storages across Queensland over 2018–20, were tested at 1 mg L^{-1} of phosphine (720 ppm) for seven days. These populations include one each from Millmerran, Dalby, Kingaroy and Roma; two from Pittsworth; and four each from Toowoomba and Townsville. Results clearly indicated that the established protocol was effective in controlling adults and immature stages of all 14 *C. maculatus* populations. This validation experiment has given us extra confidence regarding the effectiveness of the recommended dose of phosphine at 1 mg L^{-1} (720 ppm) for seven days to control *C. maculatus*.

Based on the two field trials and our validation study, we conclude that the current label rate for phosphine tablet formulation is adequate for controlling the major pulse pest, *C. maculatus* in stored mungbeans and chickpeas, provided the fumigation is undertaken over a seven day period in a high-quality sealable silo.

Figure 7: **Phosphine concentrations (ppm) measured inside a silo containing chickpeas fumigated in March 2021 at the current label rate of 1.5 tablets/m³ of silo volume for seven days**



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