KIT 1.2

Minimise the impact of spring radiation frost on grain yield and stability

Impact	**Growers in frost-prone regions manage their farm businesses to minimise the impact of frost on yield and profit.**
Summary	• Growers are aware of their options to manage frost. • Growers understand the risks and economic consequences of frost management decisions. • The innovation pipeline to tackle the constraint of frost includes digital agriculture, agronomic tools and genetics.

OVERVIEW

Spring radiation frosts (SRF) typically occur under conditions of clear skies, calm or very little wind, temperature inversion, low dew-point temperatures and air temperatures that typically fall below 0°C during the night but are above 0°C during the day. These conditions allow rapid radiation of heat to the night sky and as a result allow a drop in both soil surface temperature and the air surrounding the crop canopy (Willcocks and Stone 2000). Over the last 60 years the risk of crop damaging frost events has increased across the winter cropping regions of Australia particularly the southern and western wheatbelt. This increased frost risk is despite an increase in overall seasonal average day temperature over the past decade or two (Zheng et al. 2015; Crimp et al. 2016).

In Australia, the most damaging frosts are those that occur in spring when cereals are at post-booting stages of development (GS39 to GS71) and following bud formation in pulses and oilseeds (White 2000). However, severe frosts at earlier growth stages (e.g. stem elongation) can also cause significant damage. All winter grain crops are susceptible to spring radiation frosts (SRF) albeit to differing degrees. Oats are the least susceptible of the cereals at flowering, followed by barley and wheat is the most susceptible (White 2000). However, whilst barley is less susceptible to frost at flowering compared to wheat it is unclear whether this susceptibility difference holds for frost events occurring during grain filling. Pulses are particularly sensitive to chilling and freezing temperatures during flowering, pod formation and seed filling. Of the pulses, faba beans and lupins are less susceptible than field peas, chickpeas and lentils, although determining relative frost susceptibility in pulses is more difficult than cereals due to the indeterminate nature of these crops (Biddulph 2019). Canola is most susceptible to frost during pod filling, but the indeterminate nature of canola also provides the capacity for canola to recover from frost subject to a favourable finish.

Beyond direct yield losses, SRF can significantly impact the profitability of growers by limiting the choice of crops they can grow or when they can sow these crops. In some frost-prone regions of Australia, grain growers are choosing to sow oats and barley as the risks associated with wheat and pulse production are considered too great. In such regions, hay or pasture production is also often an important approach to managing the impact of SRF on profit. Similarly, to lower the risk of damage due to sporadic SRF events some growers delay sowing so that flowering occurs when the greatest risk of SRF has passed. However, this strategy may not maximise the use of available moisture and can in turn expose crops to later heat and water stress during grain fill. Yield losses due to delayed flowering to avoid frost can potentially be greater than those due to the direct impact of SRF (Woodruff and Tonks 1983).

The biological effects of SRF on plants and the resultant loss of production are quantifiable. However, an important but often overlooked aspect of this production constraint is the social impact on farming families and communities. The nature of SRF events (sudden and difficult to predict) can result in frost being more financially and emotionally damaging on farm businesses. Other dynamic cropping constraints such as drought generally accumulate over time and allow growers to adjust and reduce input costs to minimise losses.

SRF impact on cereals, oilseeds and pulses is a major annual production constraint for the Australian grains industry and can cause significant loss of yield and quality. Despite this, there is a paucity of data regarding the actual cost to industry of SRF in major Australian crops. Estimates based upon anecdotal reports and regional calculations had suggested that frost damage together with the impact of avoidance strategies cost the Australian grains industry approximately $400 million each year (Rebbeck and Knell 2007; Frederiks et al. 2008; Belford 2010). However, a recent crop simulation-based economic modelling study points to SRF having a greater impact than previously estimated. The study calculated that removing post head-emergence frost sensitivity in wheat alone would deliver a nation-wide annual economic benefit of at least $700 million whilst a 1°C improvement was calculated to deliver an annual economic benefit of at least $450 million (An-Vo et al. 2018). Further analysis by the GRDC Economics Business Unit, applying an aggressive discount factor for likelihood of technical success, recalculated the annual national benefit of a 1°C reduction in wheat flowering frost sensitivity to be approximately $360 million with a benefit cost ratio of 77:1 based upon the current quantum of GRDC frost investment. Similar economic analyses need to be undertaken for other grain crops.

The KIT 1.2 strategy is aligned to the grower decision-making process as it relates to SRF with a focus on investing in generation of knowledge and development of tools and technologies which support growers in frost-prone cropping regions:

A. Improve pre-season planning for SRF.
B. Make informed in-season management decisions.
C. Implement effective post-frost management responses.

FUTURE RD&E FOCUS

SCOPE – Improved pre-season planning for frost

Growers make optimal decisions on crop choice, placement and sowing in frost-prone cropping regions.

In planning their cropping operation growers in frost-prone environments are regularly seeking information on:

a. What crops and varieties to sow given knowledge of their frost susceptibility?
b. Where to sow them given knowledge of frost exposure risk across their farm?
c. When to sow based upon the phenology of the selected crop and variety and its frost sensitivity?

Current State

WHAT TO SOW

The grains industry has a broad understanding of the relative sensitivity of different grain crops to SRF (e.g. oats least susceptible and pulses the most) and use this information to guide crop selection and timing of sowing decisions.

However, the yield impact of SRF severity, duration and timing has not been defined for most grain crops as accurate frost damage functions have not been developed for winter cereals, pulses and oilseeds. The absence of accurate SRF damage functions limits industry capacity to calculate the economic impact of frost events as well as estimating the value of different frost risk and impact management options.

To date, R&D efforts to increase genetic gain for SRF have focused on wheat and barley. Variation in post head emergence frost sensitivity of wheat and barley cultivars has been reported however the relative difference between cultivars has been shown to vary in different cropping regions (Reinheimer et al. 2004; Frederiks et al. 2011/2015; Ferrante et al. 2017 and Ferrante et al. 2019). Field frost screening (phenotyping) methods have been developed and have been applied to rank the relative frost susceptibility of wheat and barley varieties (Fredricks et al. 2012; Ferrante et al. 2017) and wheat and barley variety frost rankings and these are available through the NVT website (Cocks et al. 2019). Field screening method has also been employed to screen diverse wheat germplasm from around the world with the aim of identifying germplasm that confers SRF tolerance similar to that of barley. Although variation in sensitivity to frost has been detected in local wheat varieties and international wheat germplasm, as yet no wheat germplasm has been identified with SRF tolerance equivalent to that of barley.

Low daily temperatures and frost during flowering can lead to significant flower and pod abortion in pulses and canola. Genetic improvement in cold and frost tolerance in pulses and canola during flowering will be required to support increasing genetic gain in these crops (KIT 1.4) and to facilitate their expansion into new production regions (KIT 2.1).

Genetic diversity for pulse and canola flowering cold tolerance has been reported in the international scientific literature and flowering cold tolerance has been identified in wild *cicer* (chickpea) germplasm (Berger et al. 2012). Australian use of these international genetic resources needs to be accelerated.

The current SRF tolerance field screening method has limitations in that it measures floret sterility on specific heads affected by one or more frost events and does not partition the impact of successive frosts of different duration and severity at different developmental stages. In addition, the screening method is highly labour intensive and expensive, is only applicable for cereal species and is restricted to screening the impact of SRF at flowering. These limitations are impacting the progress of pre-breeding and breeder deployment of pre-breeding outputs. New high-throughput cereal spike phenotyping technologies, including an X-ray CT system, are currently being established in Australia. However, there is an ongoing need for cheaper and higher throughput screening approaches which can accurately quantify the impact of frost on yield for a range of grain crops at different stages of development including indeterminate crops such as canola and pulses.

Breeding improved varieties for highly frost prone environments is challenging relative to other production environments due to the inherently high breeding nursery variability and failure rate typical of these environments. The development of breeding methods which improve the accuracy with which plant performance can be predicted in frost prone environments has the potential to deliver improvements in the rates of genetic gain for yield per se' in SRF prone environments. Such an approach would be complementary to efforts targeted at improved SRF tolerance.

SRF impacts yield across a broad plant development window, yet the focus of current and previous RD&E activities has been on frost damage at flowering. There is evidence for widening of the frost risk window (Zheng et al. 2015) and increasing incidence of frost damaging crops during stem elongation and grain fill. As such, a business case for expanding the current flowering frost focus needs to be undertaken to guide future investment priorities.

Advances have been made in understanding molecular and biochemical basis of variation in wheat response to cold during pollen meiosis (Barton et al. 2014; Cheong et al. 2019). However, to date there has been limited efforts made in Australia to leverage international expertise/capacity in biochemistry and regulation of vegetative tissue tolerance to cold/freezing and the impact of low temperature on development of plant reproductive structures. This is a new opportunity for R&D investment

WHERE TO SOW

Growers in frost affected cropping regions are regularly using broad knowledge of farm topography/elevation, frost event history and harvest yield data to determine what crops to plant where. However, there is an opportunity to deliver more accurate spatial temperature information so that growers can better understand SRF risk across their farm. A statistical model for mapping daily minimum temperature at a $30m^2$ spatial resolution has recently been developed and a potential approach to refine the model to predict the timing, duration and severity of frost events has been identified (Gobbett et al. 2018).

Recent GRDC supported crop phenology x elevation studies have shown that significant differences in duration of frost exposure and crop development rate can arise from modest differences in elevation of 50m or less (Gardner 2017). Opportunities exist for growers to use information such as this to improve profit by considering elevation when determining which variety maturity type or cop species to sow where and when.

Pre-seeding management practices which can affect the soil heat bank have the potential to influence frost severity and duration. The impact of stubble management on frost has been under investigation since 2013. Results to date suggest reducing stubble load can reduce the severity and duration of SRF events and that stubble load rather than stubble height, orientation or composition is the important factor (Biddulph 2019). Broad 'rules of thumb' have been produced for managing stubble to minimise frost damage without adversely impacting the well recognised beneficial aspects of stubble retention (Smith et al. 2017). Further understanding of the impact of stubble load on relative SRF damage is required.

There is anecdotal evidence that soil amelioration practices may also lessen the impact of SRF and some studies also reporting reduced frequency and duration of damaging frost events in paddocks that have been clayed, delved or spaded/moulboarded (Rebbeck et al. 2007; Butcher et al. 2017; Betti et al. 2019). However, soil amelioration can impact a range of factors, including soil water penetration, plant emergence date and nutrient availability, which confound interpretation of the potential impact of amelioration treatments on the impact of frost events on crop productivity. Carefully designed research experiments are required to determine the extent to which soil amelioration affects the severity and duration of SRF and the impact on yield.

WHEN TO SOW

Optimising sowing window and varietal selection is a key strategy employed by Australian growers to manage the risk of frost exposure and maximise yield. Despite the availability of tools such as optimum sowing time calculators many growers are continuing to choose high risk variety x sowing time combinations. In part this reflects differences in the risk appetite of individual growers and advisors as well as lack of knowledge of factors influencing the phenology of different crop varieties/ types.

GRDC and co-investment partners have and continue to invest in a range of initiatives to improve understanding of the genetic control of phenology in cereals, pulses and canola and to develop tools which improve prediction of plant development and flowering at different sowing times in different regions. There is an ongoing need for the Australian grains industry to have access to accurate phenology prediction tools to address this and other KIT's (e.g. KIT 1.5).

HOW TO SOW

Several seeding practices have been evaluated for their ability to reduce the impact of SRF, including wider row spacings/ rates, specific row direction and cross sowing. To date no compelling trial data has been generated to support the adoption of these practices as a consistent, repeatable approach to reduce the impact of SRF (Biddulph 2019).

Future Focus

GRDC will continue to invest in the development of varieties with reduced SRF sensitivity and generation of knowledge and tools that assist grain growers in optimising pre-season planning to manage frost risk. Future RD&E in this area will target the following:

Investment Outcome 1.2.1 – Growers have more accurate knowledge of the pattern and severity of frost events across the cropping landscape.

This may require farm management software providers to develop and deliver high-resolution spatial temperature mapping tools (KIT 3.2).

Investment Outcome 1.2.2 – Growers and agronomists use knowledge of the frequency and distribution of frost/ cold events to guide crop and variety selection, crop placement and planting decisions.

This may require integration of elevation data, spatial temperature dynamics data and crop damage functions. Ongoing industry access to advanced crop phenology models and tools to guide variety selection and sowing time decisions will be required.

Investment Outcome 1.2.3 – The grains industry has access to accurate information about the relationships between the severity and timing of frost events and their impact on yields of major grain crops.

The development of accurate frost damage functions (yield) for grain crops will be required to support on-farm decision making, economic modelling and frost research prioritisation. Initial focus for development of damage functions will be wheat, barley, canola, chickpeas and lentils.

Investment Outcome 1.2.4 – Growers have accurate information on the impacts of stubble load and soil management on frost severity.

Information on the economic value of stubble management, soil amelioration (overlap with KIT 1.8) and different sowing practices on frost damage in different environments and the costs:benefits associated with implementing such practices is required.

Investment Outcome 1.2.5 – Growers have access to varieties with improved yield in frost-affected cropping regions.

Greater crop choice options will require accelerated discovery of traits for enhanced yield stability under SRF. New high throughput phenotyping methods which better account for the impact of frost on yield and accelerate the discovery and use of variation for reduced frost sensitivity will need to be developed for different crop types. Increased collaboration between Australian frost researchers and international experts in complementary fields and increased exploitation of international germplasm will be required. Beyond wheat there will be an initial prioritisation of canola, chickpea and lentil consistent with the investment focus of KIT 1.4 and KIT 2.1.

Investment Outcome 1.2.6 – Plant breeders have tools to effectively reduce the frost sensitivity of major grain crops.

Breeders and pre-breeders will need to increase the accuracy and intensity of selection for frost stability traits and yield in target frost environments. This will potentially require development and application of advanced breeding tools and approaches to improve the accuracy with which plant performance in frosted environments can be predicted.

SCOPE – Informed in-season management decisions

Growers optimize type and timing of crop inputs in frost-prone cropping regions to minimize the impact of frost.

In making in-season decisions to manage frost risk growers are seeking responses to the following questions:

a. Are there forecasting tools which can accurately predict frosts early enough to inform management actions?
b. Are any of my input decisions (what I apply and timing) exacerbating or reducing damage (yield and $ impact) when a subsequent frost occurs?
c. Are there chemistries/technologies I can apply to minimise crop damage?

Current State

The capacity of grain growers to reduce the impact or risk of SRF through in season management activities is constrained by the limitations of current weather forecasting tools with accurate frost predictions limited to only 7-10 days or less. Expanded ability to forecast frost events, coupled with improved knowledge of the spatial and temporal pattern of frost risk across a farm, potentially provides improved capacity for growers to hedge input costs to better manage the risks and potential benefits of different management practices.

Recent GRDC supported research has increased our knowledge of the role of ‘blocking highs’ in frost incidence and severity (Crimp et al. 2015; Risbey et al. 2017). However, current models are unable to accurately predict the location and severity of frost events that result from blocking high pressure cells. The technical complexity of extending the predictive limits of weather/frost forecasting models beyond 10 days requires a critical mass of research capacity and as such future investment in frost forecasting research will need to engage with and leverage national and multinational climate/weather research programs.

Growers seek information regarding the impact of different management practices on the severity and duration of SRF to minimise financial risk in frost-prone paddocks. Research has been undertaken to investigate the relationship between crop nitrogen (N) and potassium (K) application practices in wheat. With respect to N, there is no evidence to date that higher rates of N increase the susceptibility of wheat to frost. It is thought that previous anecdotal reports of increased frost damage under higher N rates may be due to increased synchronisation of flowering (Biddulph 2019). Experiments with K indicate that K can potentially reduce floret sterility under frost when applied to deficient crops, however this effect was only recorded at uneconomical K concentrations and under moderate frosts based upon limited datasets (Bell 2017). Anecdotally, copper (Cu) application to Cu deficient crops has also been reported to reduce frost damage yet unequivocal experimental datasets to support this claim have not yet been produced (IPNI 2014). However, international studies have shown how copper compounds can reduce ice-nucleating bacteria and reduce frost damage in some horticultural crops (Constantindou et al. 1991). For both K and Cu, application to non-deficient crops has been reported as having no impact on frost damage.

There is considerable grower interest in the identification of chemistries/compounds which have the potential to reduce SRF damage if applied to a crop in advance of a predicted frost event. Previous screening of plant growth regulators and other products has been undertaken to assess the impact on wheat susceptibility to frost (floret sterility). To date, where an impact was measured, damage was found to be exacerbated by the application of the chemistry. However, past screening activities were structured as a service to companies and restricted to a limited number of commercially available compounds. Opportunities exist to explore a greater diversity of chemical or biological compounds through targeted partnerships with companies that own extensive chemical libraries and have international compound development and commercialisation expertise.

Grazing experiments in wheat have demonstrated that the practice of grazing can be an effective and economical alternative to delayed sowing in managing frost risk. However, the practice requires ready access to stock, specific management approaches and infrastructure and is therefore restricted in its uptake by grain producers.

Rolling of sandy and loamy clay soils post seeding has been evaluated in South Australia as a potential method to increase the soil heat bank but is not recommended as a SRF management tool based upon only limited data in support of its effectiveness and the potential downside risk associated with potential for increased erosion.

Future Focus

GRDC will continue to invest in the development of knowledge and tools that assist grain growers optimise the type and timing of crop inputs in frost-prone cropping regions to manage risk. Future RD&E in this area will target the following:

Investment Outcome 1.2.7 – The grains industry has improved in-season forecasting tools to better predict frost events and guide risk management decisions.

Opportunities for frost R&D to value-add to weather forecast tools being developed by the Bureau of Meteorology and other parties will be explored. Leverage of large national and multinational weather R&D programs will be pursued with a view to facilitating grain grower access to improved frost prediction technologies and digital agriculture products (overlap with KIT 5.1 and KIT 3.2).

Investment Outcome 1.2.8 – Growers have improved knowledge of the economic value of modifying different in-season management practices to reduce frost-related yield losses.

Sound data on the economic value of different in-season frost management practices will be required in order to support growers manage input costs relative to frost risk.

Investment Outcome 1.2.9 – Growers have access to novel and innovative in-season frost protection products.

GRDC and other Australian R&D investors partnering with companies that have proven research, freedom-to-operate and path to market expertise to facilitate the discovery and delivery of innovative frost protection products.

SCOPE – Effective post-frost responses

Growers make informed decisions regarding extracting value from frosted crops.

Following a significant SRF event, grain growers are commonly contemplating the following three questions:

a. How bad was the frost and how much damage was caused (yield reduction and $ impact)?
b. What is the likely capacity of the crop to recover given other resources such as soil moisture?
c. If the crop is badly damaged with little potential for recovery what can I do with it to maximise returns?

Current State

Current approaches for assessing crop frost damage are manual, slow and unable to account for potentially high spatial variability in damage across a grower's paddock. The development of improved methods to quantify damage is hampered by a lack of an established relationship between frost temperature/duration and impact on yield (damage function) for grain crops. Research investigating the utility of spectral indices to identify frost damage in wheat has commenced Perry et al. 2017; Fitzgerald et al. 2019). Although indices related to freezing temperatures have been identified, these vary by tissue and variety and currently it is unknown whether they would allow differentiation of frost from other plant stresses.

Beyond broad 'rules of thumb' there is uncertainty as to the capacity of different crops to compensate for frost damage and a lack of experimental data and published methods to assist growers assess the potential for crop recovery under different soil moisture scenarios.

Recent studies have investigated post-frost salvage options for frosted wheat, including grazing and cutting for hay but similar data has not been generated for other crops such as canola. To date, the critical damage thresholds to enact these management options over harvesting (including level and timing of damage) and approaches to maximise the economic value of salvage options in different systems and regions has not been clearly defined and/or extensively communicated.

Future Focus

GRDC will continue to invest in the development of knowledge and tools that assist grain growers make better- informed decisions regarding extracting value from SRF affected crops. Future RD&E will target the following:

Investment Outcome 1.2.10 – Growers have access to accurate measurement tools to quantify yield loss following frost.

Frost sensing and measurement tools will need to enable growers to rapidly, accurately and spatially quantify frost yield loss in winter cereal, oilseed and pulse crops (overlap with KIT 3.2). This will likely require integration of frost severity data, crop development, soil moisture and other environmental data. Additionally, growers and their advisors will require tools to estimate the recovery potential of different frosted crops. Sound experimental data describing how the timing and severity of frost impact the recovery potential of different crops, in the context of other limiting resources such as soil moisture, will be required. To support grower decisions, tools will need to be cost-effective and deliver accurate data in short timeframes and at a spatial resolution relevant to grower operations.

Investment Outcome 1.2.11 – Growers have knowledge of the economic value of different salvage options and management practices which can be applied to frost-affected crops.

Improved knowledge of the value of different crop salvage options combined with accurate spatial frost damage data, provides opportunities for growers to make better informed post-frost management decisions. Accurate economic data for options including hay production (to maximise quality), grazing, crop topping, manuring and alternative biomass utilisation approaches in different cropping regions will be required. Opportunities for partnership and co-investment with feed/biomass-focussed industries will need to be explored.

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