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Project Code	
Project Type	

FINAL REPORT 2017

PROJECT CODE	:	S416

PROJECT TITLE

Burning of weed seeds in low rainfall farming systems

PROJECT DURATION

Project Start date	1 July 2016					
Project End date	31 December 2017 (per variation agreement)					
SAGIT Funding Request	2014/15	$	2015/16	$	2016/17	

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PROJECT REPORT

Executive Summary

Burning crop residues to destroy weed seeds is one of the oldest cultural weed control measures in agriculture. While information exists on annual ryegrass and wild radish, very little is known about the potential efficacy of burning other weed species that impact on low rainfall cropping systems in southern Australia. A study was conducted to simulate stubble burning by treating weed seeds to high temperatures for differing durations. Seeds of all species could be killed with heat, however there were differences in tolerance to heat. Duration of heat treatments had a significant impact on the efficacy on weed seeds in all species. Seeds of most weed species could be killed by simulating conditions similar to burning narrow windrows that can achieve high temperatures for prolonged durations. Variation in the efficacy of narrow windrow burning observed in the field is likely to be related to the differences in weed seeds that can be collected at harvest and placed into harvest windrows.

Project Objectives

- Determine temperature thresholds for killing the seeds of common weeds for low rainfall farming systems in South Australia.
- Enable farmers to assess the value of narrow windrow and other burning strategies as integrated management tools for these weeds and ultimately to manage weeds more effectively.

Overall Performance

The project was successful in determining temperature (and time) thresholds for killing the seeds of the following weed species from low rainfall farming systems:

- Lincoln weed
- Indian Hedge mustard
- Onion weed
- Barley grass
- Brome grass
- Statice
- Annual ryegrass
- Wild turnip
- Mallow

The information has been presented to farmers via articles in regional compendiums of Eyre Peninsula [Attachment 2, 3], SA/VIC/NSW Mallee and Upper North. Information has been presented to farmers at Harvest Report farmer meetings across the upper Eyre Peninsula and the SA/VIC/NSW Mallee.

Difficulties:

- Delays in delivery due to issues with obtaining the kiln from the US in a timely manner and hard wiring of kiln took longer than anticipated.
- Changes of personnel within MSF meant the opportunity to gather burning temperature data in that region was missed.
- Wild oats seeds had issues with germination (even without burning), and so were excluded from the burning trials.

Co-operators:

- SARDI (Naomi Scholz, sub-contracting and project coordination; Amanda Cook, collection of weed seeds from EP, development of field burning measurement protocols [Attachment 1], collection of field burning data)
- University of Adelaide (Ben Fleet, determining temperature/time thresholds, provision of report [Appendix 1])
- MSF (Stuart Putland, collection of weed seeds for burning)
- UNFS (Ruth Sommerville/Barry Mudge, collection of weed seeds for burning, collection of field burning data)

Key Performance Indicators (KPI)

KPI	*Achieved (Y/N)*	*If not achieved, please state reason.*
Kleeman weed seeds exposed to kiln temperatures and germinated	Y	10 weed species tested. 9 species reported (Wild oats excluded from results, issues with germination).
FS groups and SARDI collected weed seeds	Y	MSF, UNFS and SARDI (upper EP) supplied weed seeds for testing.
Project collected seeds exposed to kiln temperatures	Y	10 weed species tested.

All weed seed samples assessed for changes in dormancy	N	Dormant weed populations were not used in this study as they would have confounded weed seed kill results. The effect of heat on weed seed germination were examined over the range of temperatures and durations. Only barley grass and brome grass showed small increase in germination when exposed to short durations of heat treatment, but this was non-significant.
FS groups and SARDI monitored field burns	Partial	Changes of personnel within MSF meant the opportunity to gather burning temperature data in that region was missed. Field burn measurements conducted by SARDI (upper EP) and UNFS.
Final report submitted	Y	

Technical Information

Table 1. Paddock details, crop type, stubble and weather conditions at burning in autumn 2017.

Burning date	Crop	Crop yield (t/ha)	Paddock	Burn type	Stubble height (cm)	Stubble load (t/ha)	Relative humidity (%)	Wind speed and direction (km/h)	Temperature (°C)
20 March	Mace wheat	3.0	MAC S1	windrows	18	2-3	16	10 WNW	30
28 April	Mace wheat	3.3	MAC S7	windrows	19	2-3	17	9 SSE	19
26 April	Compass barley*	4.0	MAC Airport	windrows	22	2.5-3.5	38	28 SSW	16
26 April	Mace wheat*	2.8	MAC Airport	windrows	19	2-3	38	28 SSW	16
17 March	Trojan wheat	2.6	MAC S4	windrows	17	2-3	17	9 S	29
17 March	Mace wheat	3.6	MAC N5S	windrows	15	2-3	17	9 S	29
10 May	Medic and barley grass	3.7 DM hay cut	MAC N1	large plots - paddock burn (9 m x 9 m)	17	3-4	23	15 NNE	19
10 May	Mace wheat	2.9	MAC N1	windrows	17	2-3	23	15 NNE	19
9 May	UNFS Canola	2.3	Nottle Paddock 1	windrows	40	1-2	36	7 NNE	20
9 May	UNFS Canola	2.1	Nottle Paddock 2	windrows	40	3-4	27	4 NNE	21
5 May	UNFS Wheat	NA as leased	Hazels	windrows	40	5-6	36	8 NE	19
5 May	UNFS Wheat	NA as leased	Hazels	paddock burn	40	5-6	36	8 NE	19

***11 mm received between 20-27 April*

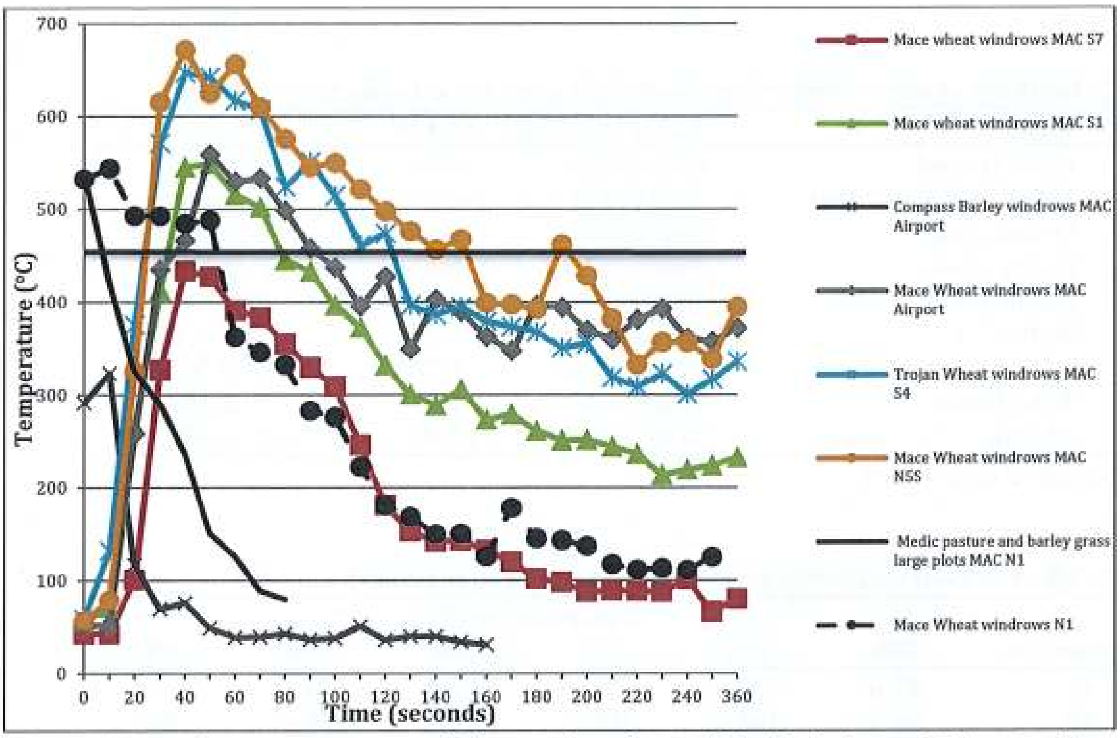

Figure 1. Burning temperatures (°C) over time (seconds) of windrows (wheat and canola) prior to seeding in 2017 at Minnipa Agricultural Centre.

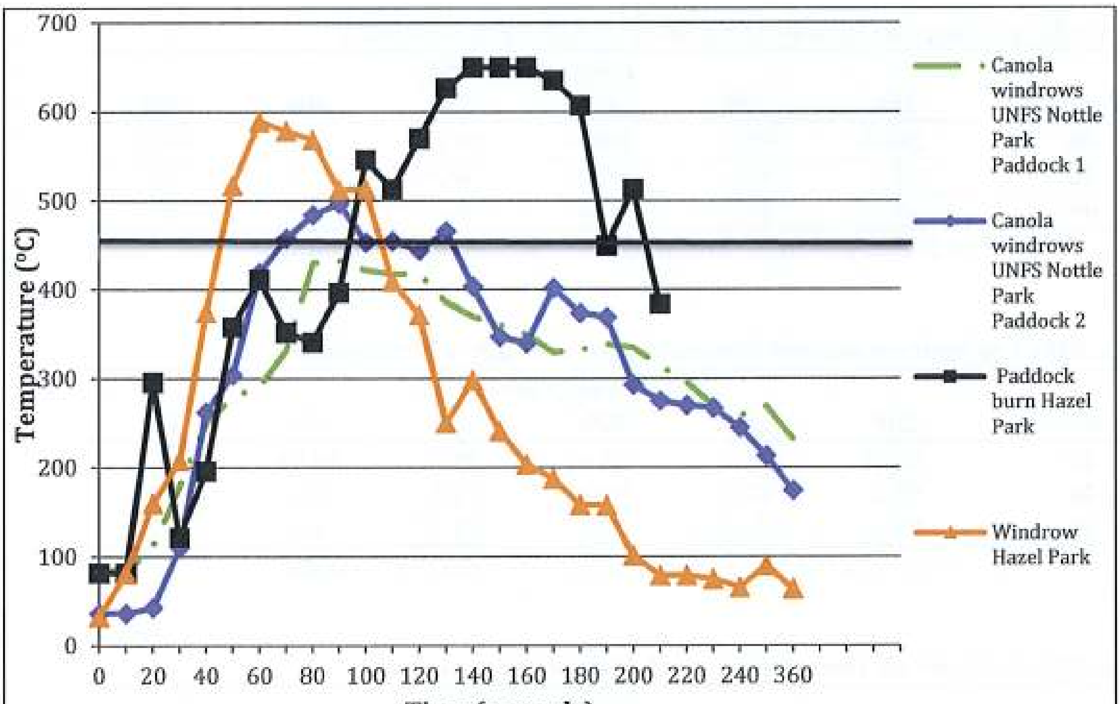

Figure 2. Burning temperatures (°C) over time (seconds) of windrows (wheat and canola) prior to seeding in 2017 in the Upper North, SA.

[SOURCE: Attachment 2 Burning temperatures of harvest windrows and standing stubbles]

Table 2. Ranking of weed seed tolerance to heat from least to the most tolerant.

Rank	Weed	X_0 for HI *(SEM)*	HI R^2	P
1	Lincoln weed	6231 *(325)*	0.78	*P<0.0001*
2	Indian Hedge Mustard	10021 *(929)*	0.70	*P<0.0001*
3	Onion weed	15028 *(391)*	0.77	*P<0.0001*
4	Barley grass	16043 *(373)*	0.82	*P<0.0001*
5	Brome grass	16070 *(562)*	0.73	*P<0.0001*
6	Statice	16618 *(298)*	0.88	*P<0.0001*
7	Annual ryegrass	17505 *(474)*	0.78	*P<0.0001*
8	Wild Turnip	18405 *(484)*	0.74	*P<0.0001*
9	Mallow	21197 *(1413)*	0.44	*P<0.0001*

SEM - Standard error mean

Table 3. Effect of heat on Barley grass seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	97 *a*	100 *a*	97 *a*	97 *a*	94 *a*	57 *bc*
40	96 *a*	100 *a*	100 *a*	62 *b*	**19 *d***	**0 *e***
60	97 *a*	96 *a*	51 *c*	**0 *e***	**0 *e***	**0 *e***

P<0.001, LSD=9.666, cv rep=5.6%, >80% reduction bolded

Table 4. Effect of heat on Brome grass seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	100 *a*	98 *a*	100 *a*	91 *a*	71 *b*	68 *b*
40	97 *a*	93 *a*	98 *a*	59 *b*	7 *c*	**0 *c***
60	98 *a*	89 *a*	72 *b*	**2 *c***	**0 *c***	**0 *c***

P<0.001, LSD=16.07, cv rep=5.8%, >80% reduction bolded

Table 5. Effect of heat on Annual Ryegrass seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	93 *ab*	98 *a*	98 *a*	98 *a*	93 *ab*	70 *b*
40	98 *a*	97 *a*	99 *a*	73 *b*	54 *c*	**0 *e***
60	99 *a*	95 *ab*	82 *b*	21 *d*	**1 *e***	**0 *e***

P<0.001, LSD=14.44, cv rep=3.2%, >80% reduction bolded

Table 6. Effect of heat on Onion weed seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	94 *ab*	93 *ab*	88 *ab*	90 *ab*	82 *b*	38 *c*
40	91 *ab*	89 *ab*	91 *ab*	31 *c*	**1 *d***	**0 *d***
60	87 *ab*	86 *ab*	**11 *d***	**0 *d***	**0 *d***	**0 *d***

P<0.001, LSD=15.31, cv rep=7.9%, >80% reduction bolded

Table 7. Effect of heat on Statice seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	96 *ab*	95 *ab*	96 *ab*	100 *a*	99 *a*	83 *b*
40	98 *ab*	92 *ab*	97 *ab*	76 *b*	46 *c*	**4 *e***
60	94 *ab*	91 *ab*	48 *c*	24 *d*	**2 *e***	**4 *e***

*P<0.001, LSD=14.50, cv rep=3.3%, >80% reduction **bolded***

Table 8. Effect of heat on Mallow seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	100 *a*	92 *ab*	95 *ab*	100 *a*	100 *a*	100 *a*
40	97 *ab*	75 *ab*	100 *a*	100 *a*	92 *ab*	**3 *c***
60	92 *ab*	88 *ab*	95 *ab*	44 *b*	66 *b*	**9 *c***

*P<0.001, LSD=32.26, cv rep=3.1%, >80% reduction **bolded***

Table 9. Effect of heat on Lincoln weed seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	97 *a*	92 *a*	62 *b*	**11 *c***	**0 *c***	**0 *c***
40	49 *b*	**18 *c***	**0 *c***	**0 *c***	**0 *c***	**0 *c***
60	**18 *c***	**3 *c***	**0 *c***	**0 *c***	**0 *c***	**0 *c***

*P<0.001, LSD=28.87, cv rep=17.1%, >80% reduction **bolded***

Table 10. Effect of heat on Indian Hedge Mustard seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	71 *b*	66 *bc*	88 *a*	54 *c*	69 *b*	**0 *e***
40	73 *b*	53 *c*	47 *c*	**0 *e***	**0 *e***	**0 *e***
60	69 *b*	**19 *d***	**1 *e***	**0 *e***	**1 *e***	**0 *e***

*P<0.001, LSD=12.55, cv rep=4.2%, >80% reduction **bolded***

Table 11. Effect of heat on Wild Turnip seed viability (% survival).

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	98 *a*	98 *a*	98 *a*	100 *a*	100 *a*	99 *a*
40	99 *a*	99 *a*	98 *a*	99 *a*	92 *a*	**0 *c***
60	100 *a*	99 *a*	98 *a*	32 *b*	**0 *c***	**0 *c***

*P<0.001, LSD=21.40, cv rep=3.7%, >80% reduction **bolded***

[SOURCE: Appendix 1 S416 – Burning of weed seeds in low rainfall farming systems – University of Adelaide report]

Conclusions Reached &/or Discoveries Made

- Seeds of Lincoln weed, Indian Hedge mustard, Onion weed, Barley grass, Brome grass, Statice, Annual ryegrass, Wild turnip and Mallow could be killed with heat, however there were differences in tolerance to heat.
- Duration of heat treatments had a significant impact on the efficacy on weed seeds in all species tested.
- Cereal windrow burning achieved temperatures in excess of those required to achieve high levels of weed seed mortality, except in paddocks which had 11 mm of rainfall the week before.
- The efficacy of narrow windrow burning in the field is largely determined by the proportion of weed seeds that can be collected by the header and placed into harvest windrows.
- The open paddock burn with a high stubble load had a faster burn but still achieved the necessary temperatures of 450°C for longer than 60 seconds.

The results from the paddock burning measurements, using hand held temperature gun, showed that, when dry, in most situations temperatures achieved when burning narrow harvest windrows were likely to achieve good control of the weed seeds collected in the harvest row. Total control of weed seeds across the paddock using these methods will depend on the proportion of the weed seeds that can be collected by the harvest operation.

Intellectual Property

No novel commercial IP was generated in this project.

Application / Communication of Results

Main findings

- Seeds of Lincoln weed, Indian Hedge mustard, Onion weed, Barley grass, Brome grass, Statice, Annual ryegrass, Wild turnip and Mallow could be killed with heat, however there were differences in tolerance to heat.
- Duration of heat treatments had a significant impact on the efficacy on weed seeds in all species tested.
- Cereal windrow burning achieved temperatures in excess of those required to achieve high levels of weed seed mortality, except in paddocks which had 11 mm of rainfall the week before.
- The efficacy of narrow windrow burning in the field is largely determined by the proportion of weed seeds that can be collected by the header and placed into harvest windrows.
- The open paddock burn with a high stubble load had a faster burn but still achieved the necessary temperatures of 450°C for longer than 60 seconds.

Potential industry impact

The project results have provided confidence for growers that a hot burn (best achieved by placing residues in windrows and burning when dry) over 60 seconds will effectively kill weed seeds of Lincoln weed, Indian Hedge mustard, Onion weed, Barley grass, Brome grass, Statice, Annual ryegrass, Wild turnip and Mallow. This provides farmers with one tool for control in an integrated weed management approach.

Publications and extension articles

The key messages from the burning weed seed project were presented to 141 people made up of 120 farmers, 21 agribusiness representatives, and 1 NRM staff member at Minnipa, Piednippie, Charra, Pt Kenny, Kimba, Cowell, Rudall and Warramboo farmer meetings held in March 2018.

Articles were published in the Eyre Peninsula Farming Systems Summary (distribution 1100), Mallee Sustainable Farming Compendium (150) and Upper North Farming Systems Annual Summary (110) in 2018 (pending).

Articles are also available on the EPARF, MSF and UNFS websites.

- Fleet, Kleemann, Gill (2018) *Burning of weed seeds in low rainfall farming systems.* Eyre Peninsula Farming Systems Summary 2017, p 72.
- Cook, Fleet, Scholz (2018) Burning temperatures of harvest windrows and standing stubbles in low rainfall farming systems. Eyre Peninsula Farming Systems Summary 2017, p 78.
- Cook, Fleet, Scholz (2018) Burning temperatures of harvest windrows and standing stubbles in low rainfall farming systems. Mallee Sustainable Farming 2017.
- http://www.msfp.org.au/wp-content/uploads/Burning-temperatures-of-harvest-windrows-in-low-rainfall-farming-systems-Amanda-Cook-Full.pdf (Accessed 21/02/2017)
- http://eparf.com.au/wp-content/uploads/2018/05/2a.-Burning-of-weed-seeds-in-low-rainfall-farming-systems-FLEET.pdf (Accessed 01/05/2018)
- http://eparf.com.au/wp-content/uploads/2018/05/2b.-Burning-temperatures-of-harvest-windrows-and-standing-stubbles-in-LRFS-COOK.pdf (Accessed 01/05/2018)
- Upper North Farming Systems to publish articles in their 2018 compendium (2017 results) (yet to be published at time of reporting).

Path to market

Although burning has been shown to be effective in killing seeds of common weeds, it would still be considered a 'last resort' option in the control of weeds in low rainfall farming systems.

Advantages of burning: effective; aside from labour, burning does not require input costs such as herbicide use (less input cost, reduced risk of resistance development) and fuel costs (spraying operation).

Disadvantages: social license issues (burning becoming less socially acceptable); potential for bushfire risk; work, health and safety risks, increasing labour and equipment requirements to meet CFS guidelines/codes of conduct; administrative requirements e.g. permits.

Alternatives: chaff lining (where chaff including weed seeds is placed directly on wheel tracks and allowed to rot rather than burning) is gaining popularity, particularly in WA.

POSSIBLE FUTURE WORK

- *How much weed seed are we collecting at harvest to place into windrows?* Currently being investigated by University of Adelaide and SARDI Minnipa Agricultural Centre.
- *Does swathing crops enable greater collection of weed seeds for harvest weed seed control?* Currently being investigated (S117).
- *Is chaff lining an effective method of harvest weed seed control?* Currently developing GRDC Innovation submission for research funding. University of Adelaide have a small GRDC project to measure seed capture.

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Signature:	
Date:	14.08.2018

ATTACHMENTS:

1. Weed seed collection and paddock burning protocol
2. Burning temperatures of harvest windrows and standing stubbles (EPFS Summary article)
3. Burning of weed seeds in low rainfall farming systems (EPFS Summary article)

APPENDIX 1
S416 – Burning of weed seeds in low rainfall farming systems – University of Adelaide report

Ben Fleet, Samuel Kleemann, and Gurjeet Gill
University of Adelaide, School of Agriculture, Food and Wine

Abstract
Burning crop residues to destroy weed seeds is one of the oldest cultural weed control measures in agriculture. While information exists on annual ryegrass and wild radish, very little is known about the potential efficacy of burning on other weed species that impact on low rainfall cropping systems in southern Australia. A study was conducted to simulate stubble burning by treating weed seeds to high temperatures for differing durations. Seeds of all species could be killed with heat, however there were differences in tolerance to heat. Duration of heat treatments had a significant impact on the efficacy on weed seeds in all species. Seeds of most weed species could be killed by simulating conditions similar to burning narrow windrows that can achieve high temperatures for prolonged durations. Variation in the efficacy of narrow windrow burning observed in the field is likely to be related to the differences in weed seeds that can be collected at harvest and placed into harvest windrows.

Introduction
Weeds are one of the largest costs to grain producers and a primary driver in how cropping systems are managed. Weeds are estimated to cost Australian grain growers $3,318 million annually (Llewellyn et al. 2016). Weeds will continue to drive crop management systems as weed challenges evolve, particularly from herbicide resistance. This will increase the importance of cultural control methods as part of any integrated weed management (IWM) strategies. Burning crop residues to destroy weed seeds is one of the oldest cultural weed control measures in agriculture. While information exists on annual ryegrass and wild radish efficacy from burning crop residues (Gill and Holmes, 1997; Walsh and Newman, 2007), little is known about other weed species. This study aims to investigate the potential of crop residue burning to control weeds that are problematic for low rainfall cropping systems in southern Australia. A method similar to Walsh and Newman (2007) was used to simulate different levels of heat (temperature) and duration experienced during crop residue burning on weed seeds.

Materials and Methods
Seed collection
Seeds of 10 different weed species were collected from cropping fields at weed maturity (Table 1). Seed was cleaned and removed from associated structures for all species except Mallow that was left in individual seed pod segments. This was done to achieve consistency with the state of weed seeds shedding and at the time of stubble burning. Seeds were counted and placed into packets of 100 seeds.

Table 1. Weed seeds and district of origin

Weed species	Region
Barley grass *Hordeum glaucum*	Upper Eyre Peninsula
Brome grass *Bromus diandrus*	*Northern Yorke Peninsula & Mallee
Wild Oats *Avena fatua - (1)*	Lower North
Wild Oats *Avena fatua – (2)*	Upper Eyre Peninsula
Annual ryegrass *Lolium rigidum*	# 'safeguard ARG' control species
Onion weed *Asphodelus fistulosus*	Upper Eyre Peninsula
Statice *Limonium lobatum*	Upper North
Mallow *Malva parviflora*	Upper North
Indian Hedge Mustard *Sisymbrium orientale*	Lower North
Lincoln weed *Diplotaxis tenuifolia*	Upper Eyre Peninsula
Wild Turnip *Brassica tournefortii*	* Mallee & Upper North

* composite population, Mallow was treated in individual seed pod segments

Heat treatment

A kiln (Woodrow GK63TL top loading glass kiln) was used to apply heat treatments to seeds. The kiln was preheated to the desired temperature. Seed of each species were placed in a ceramic dish, held in a rack and swiftly placed into the kiln for the desired duration. Seed was allowed to cool in the dishes and placed back into their packets for later germination assessment. Temperature readings from the kiln were calibrated against a laboratory infrared thermometer (MIKRON IR-MAN model 15t) shown below in table 2.

Table 2. Kiln temperature calibration against laboratory infrared thermometer (IRT)

Kiln temp	200°C	250°C	300°C	350°C	400°C	450°C
IRT temp	200.1°C	246°C*	300°C	355.3°C	400.6°C	451°C

IRT temp mean of multiple readings, * kiln set to 255°C to achieve correct temperature

Germination assessment

Treated seed packets were placed in petri-dishes (Sigma-Aldrich 150 x 15 P5891) with 2 filter paper discs on the base (Whatman 1 150mm circle 1001-150). 10mm of 0.001M Gibberellic acid (GA) (Sigma-Aldrich G7645 Gibberellic acid) solution was applied to the seed, brome grass and barley grass requiring 12.5mm and wild oats requiring 15mm GA solution. Dishes were then sealed with parafilm (Sigma-Aldrich PM-992 P7543 parafilm) and then all 19 dishes (single rep of each weed species) was wrapped in two layers of aluminium foil and placed into a controlled environment growth room (Phoenix systems) at 20°C / 12°C day / night temperature for approximately 14 days at which time both germinated and non-germinated seeds were counted. At 14 days mallow seeds were counted and individual seeds were removed from seed pod segments. Mallow seeds that were deemed to be potentially viable (still hard), but not germinated were knicked with a scalpel and placed back onto dishes with fresh GA solution and returned to growth room for a further 7 days when germination was again assessed. Wild oat populations were given extended time in the growth room, but failed to germinate and were excluded from the trial.

Trial details and analysis

The trial was replicated three times with 100 seeds in each sample. Germination in each dish was compared back to the relevant untreated control. This was then statistically analysed using an analysis of variance using GENSTAT 15th Edition statistical computer program.

Results and Discussion

The ability of weed seeds to tolerate heat varied considerably between species with Lincoln weed seed being the most susceptible and mallow seed being the most tolerant to heat (Table 2.). Germination data was plotted against a heat index (HI = temperature ºC x duration seconds), and a sigmoidal logistic 3 parameter model was fitted using SigmaPlot 12.5 v002 statistical program. Parameter X_0 from the fitted model represents the HI units required to suppress seed germination by 50%. X_0 values were used to rank weed species for tolerance to heat. Tolerance of weed seeds to heat was not closely related to seed size or weed type. Brassica seeds with their smaller size and high oil content would be expected to be more sensitive to heat. This was the case for both Lincoln weed and Indian hedge mustard (IHM) which were the two most susceptible weed species to heat. However wild turnip, another brassica weed, was the second most tolerant species studied. Larger seed size did not correlate with tolerance to heat, with smaller seeded ryegrass showing greater tolerance to heat than larger brome or barley grass seeds.

Table 3. Ranking of weed seed tolerance to heat from least to the most tolerant

Rank	Weed	X_0 for HI *(SEM)*	HI R^2	P
1	Lincoln weed	6231 *(325)*	0.78	*P<0.0001*
2	Indian Hedge Mustard	10021 *(929)*	0.70	*P<0.0001*
3	Onion weed	15028 *(391)*	0.77	*P<0.0001*
4	Barley grass	16043 *(373)*	0.82	*P<0.0001*
5	Brome grass	16070 *(562)*	0.73	*P<0.0001*
6	Statice	16618 *(298)*	0.88	*P<0.0001*
7	Annual ryegrass	17505 *(474)*	0.78	*P<0.0001*
8	Wild Turnip	18405 *(484)*	0.74	*P<0.0001*
9	Mallow	21197 *(1413)*	0.44	*P<0.0001*

Grass weeds

Barley grass has become a serious weed of many low rainfall cropping systems due to increased seed dormancy and incidence of herbicide resistance (Fleet et al. 2012; Shergill et al. 2015). The effect of heat, like that produced from burning crop residues, on barley grass was found to be strongly influenced by both temperature and duration (Table 4). Barley grass seed was completely killed at 350ºC, but only at a duration ≥60 seconds. However, barley grass seed kill was significantly reduced at shorter durations. Exposure of barley grass seeds to 300ºC for a duration of 60 seconds could halve barley grass seed viability. However, the same level of control could be achieved by exposure to >450ºC for 20 seconds. Based on the results of stubble burn temperatures from Walsh and Newman (2007), effective control of barley grass seed is only expected in heavy windrows or narrow windrows. Burning a standing stubble is unlikely to be effective in killing barley grass seed. Unfortunately, most barley grass seed has shed well before crop harvest and is unlikely to end up in the windrow for burning or captured by harvest weed seed capture (HWSC) systems. In a field trial in the UN, Fleet et al. (2014) found that when wheat was harvest-ready, < 1% of barley grass had the potential of being collected, with the remainder either being shed onto the ground or below 10cm in height. Similar results were found in plot studies where <6% of barley grass seed remained on the panicles when wheat was harvest-ready (Kleemann et al. 2016). Therefore, the effectiveness of windrow burning against barley grass is expected to be rather low.

Table 4. Effect of heat on Barley grass seed viability

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	97 *a*	100 *a*	97 *a*	97 *a*	94 *a*	57 *bc*
40	96 *a*	100 *a*	100 *a*	62 *b*	19 *d*	0 *e*
60	97 *a*	96 *a*	51 *c*	0 *e*	0 *e*	0 *e*

P<0.001, LSD = 9.666, cv rep = 5.6%, >80% reduction highlighted

The response of brome grass to high temperature exposure was very similar to barley grass (Table 5). Effective kill of brome grass seed is also likely to require crop stubble to be burnt in either a heavy row or narrow windrow to achieve required temperatures and duration of heat. Contrary to barley grass brome grass is capable of retaining 75% of its seed on the panicle by earliest crop harvest. However brome grass plants can often lodge and fall below the harvest cutting height. In a field trial at Roseworthy, depending on weed density, 30-80% of brome grass panicles were below the height of crop harvest at earliest crop harvest (Kleemann et al. 2016). Despite this, HWSC followed by burning of windrows could provide some level of control of brome grass.

Table 5. Effect of heat on Brome grass seed viability

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	100 *a*	98 *a*	100 *a*	91 *a*	71 *b*	68 *b*
40	97 *a*	93 *a*	98 *a*	59 *b*	7 *c*	0 *c*
60	98 *a*	89 *a*	72 *b*	2 *c*	0 *c*	0 *c*

P<0.001, LSD = 16.07, cv rep = 5.8%, >80% reduction highlighted

While ARG seed was found to be the most heat tolerant of the grass weeds trialled (Table 3.), it followed a similar trend to brome and barley grass (Table 6.). ARG required approximately 100°C more heat at equivalent duration than either brome or barley grass to achieve a high level of weed seed control. These results show ARG to be more tolerant to heat than previously reported by Walsh and Newman (2007). Given the temperatures required to control ARG seeds, HWSC tactics where harvest residue is placed in heavy rows or preferably narrow windrows for burning would be required. A South Australian study of the potential of HSWC tactics found that between 26-73% of annual ryegrass seed could potentially be captured and then placed in narrow windrows for burning (Fleet et al. 2014). While still highly variable, depending on the timing and seasonal conditionals, ARG has the potential for significant seed control with HWSC tactics and narrow windrow burning. Ranking of these grass species would be barley grass: unviable < brome grass some control < annual ryegrass moderate control.

Table 6. Effect of heat on Annual Ryegrass seed viability

Duration (s)	Temperature (°C) 200	250	300	350	400	450
20	93 *ab*	98 *a*	98 *a*	98 *a*	93 *ab*	70 *b*
40	98 *a*	97 *a*	99 *a*	73 *b*	54 *c*	0 *e*
60	99 *a*	95 *ab*	82 *b*	21 *d*	1 *e*	0 *e*

P<0.001, LSD = 14.44, cv rep = 3.2%, >80% reduction highlighted

Broadleaf weeds

Onion weed seed was more sensitive to heat than the grass species studied (Table 7.). Onion weed is usually found in areas of poor competition in crops and pastures (Pitt et al. 2006). Despite the potential of heat to control onion weed seeds it could be difficult to have enough crop or pasture biomass to achieve enough heat and duration for effective control, particularly if burning pasture residues or standing stubble. Such paddocks are also prone to wind erosion so the implications of burning need to be considered carefully.

Table 7. Effect of heat on Onion weed seed viability

Duration (s)	Temperature (°C) 200	250	300	350	400	450
20	94 *ab*	93 *ab*	88 *ab*	90 *ab*	82 *b*	38 *c*
40	91 *ab*	89 *ab*	91 *ab*	31 *c*	1 *d*	0 *d*
60	87 *ab*	86 *ab*	11 *d*	0 *d*	0 *d*	0 *d*

P<0.001, LSD = 15.31, cv rep = 7.9%, >80% reduction high lighted

Statice seed was significantly more tolerant of heat than onion weed (Table 3.). It required temperatures ≥400°C for 60 s duration to achieve effective control of statice seeds. From the stubble burning temperatures reported in Walsh & Newman (2007), HWSC and narrow windrow burning would be required to possibly achieve effective control of statice seed. This species shows potential of HWSC techniques as it appears to retain seed pods and is often a grain contaminant in problem paddocks, however will require very hot and prolonged stubble burning conditions. As statice is often found in paddocks affected by some level of salinity, the level of crop residue present may be inadequate for achieving prolonged hot burn.

Table 8: Effect of heat on Statice seed viability

Duration (s)	Temperature (°C) 200	250	300	350	400	450
20	96 *ab*	95 *ab*	96 *ab*	100 *a*	99 *a*	83 *b*
40	98 *ab*	92 *ab*	97 *ab*	76 *b*	46 *c*	4 *e*
60	94 *ab*	91 *ab*	48 *c*	24 *d*	2 *e*	4 *e*

P<0.001, LSD = 14.50, cv rep = 3.3%, >80% reduction highlighted

Mallow seed was treated in small pod segments as by autumn when crop residues are burnt the primary mallow pods have broken up and individual pod sections remain. Mallow was found to be extremely heat tolerant and would likely prove very difficult to control in many stubble burning situations. It was found to require ≥450°C for ≥40 seconds to obtain effective control of seeds (Table 9.). At 450°C there was no seed kill at 20 seconds duration, but high levels of control at 40 seconds duration, indicating a critical heat duration time between 20-40 seconds at this temperature. Mallow was the most heat tolerant weed species in this study (Table 3.).

Table 9: Effect of heat on Mallow seed viability

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	100 *a*	92 *ab*	95 *ab*	100 *a*	100 *a*	100 *a*
40	97 *ab*	75 *ab*	100 *a*	100 *a*	92 *ab*	3 *c*
60	92 *ab*	88 *ab*	95 *ab*	44 *b*	66 *b*	9 *c*

P<0.001, LSD = 32.26, cv rep = 3.1%, >80% reduction highlighted

Brassica weeds

Lincoln weed seed was found to be the most sensitive weed species to high temperature exposure in this study (Table 3.). Like other species, Lincoln weed seed control was dependent on both temperature and duration. However once temperature was ≥350°C, effective control could be achieved even with 20 s exposure (Table 10.). This indicates that there would be some potential to control Lincoln weed in standing stubble situations. An additional complication would be that such a small seed could fall between soil clods or cracks and be insulated from any heat caused by burning. Walsh and Newman (2007) reported that as little as 1cm of soil cover could effectively insulate seed from heat produced from residue burning. Lincoln weed would not be suited for HWSC and narrow windrow burning as it is generally a weed of summer fallows where it grows after crop harvest.

Table 10: Effect of heat on Lincoln weed seed viability

	Temperature (°C)					
Duration (s)	**200**	**250**	**300**	**350**	**400**	**450**
20	97 *a*	92 *a*	62 *b*	11 *c*	0 *c*	0 *c*
40	49 *b*	18 *c*	0 *c*	0 *c*	0 *c*	0 *c*
60	18 *c*	3 *c*	0 *c*	0 *c*	0 *c*	0 *c*

P<0.001, LSD = 28.87, cv rep = 17.1%, >80% reduction high lighted

IHM seed was found to be more tolerant of heat than Lincoln weed (Table 3.). While temperatures ≥450°C could completely control IHM seed at the shorter duration times, duration times of ≥60 seconds were required to achieve effective control at 250-300°C (Table 11.). According to the temperature and duration results reported by Walsh and Newman (2007), potentially enough heat would be generated for long enough to effectively control IHM seed when either burning heavy conventional or narrow harvest windrows. IHM is also well suited for HWSC followed by windrow burning as it has high pod and seed retention (Fleet et al. 2016).

Table 11: Effect of heat on Indian Hedge Mustard seed viability

	Temperature (°C)					
Duration (s)	200	250	300	350	400	450
20	71 *b*	66 *bc*	88 *a*	54 *c*	69 *b*	0 *e*
40	73 *b*	53 *c*	47 *c*	0 *e*	0 *e*	0 *e*
60	69 *b*	19 *d*	1 *e*	0 *e*	1 *e*	0 *e*

P<0.001, LSD = 12.55, cv rep = 4.2%, >80% reduction high lighted

Wild turnip seed was found to be one of the most heat tolerant of the weed species studied, particularly when compared to other brassica weeds. Wild turnip was nearly 2 and 3 fold more tolerant than IHM and Lincoln weed, respectively (Table 3.). Wild turnip required ≥400°C for 60 seconds to effectively kill seeds; a 40 second duration achieved the same results when temperature was increased to 450°C. However at 450°C, 20 second heat duration had no effect on seed viability (Table 12). Narrow windrow burning of stubble would be the only way to potentially achieve the temperatures and durations required to effectively control wild turnip seed (Walsh and Newman, 2007). Wild turnip is unlikely to be well suited to HWSC and narrow windrow burning as it is prone to shed seeds early before crop harvest.

Table 12: Effect of heat on Wild Turnip seed viability

	Temperature (°C)					
Duration (s)	200	250	300	350	400	450
20	98 *a*	98 *a*	98 *a*	100 *a*	100 *a*	99 *a*
40	99 *a*	99 *a*	98 *a*	99 *a*	92 *a*	0 *c*
60	100 *a*	99 *a*	98 *a*	32 *b*	0 *c*	0 *c*

P<0.001, LSD = 21.40, cv rep = 3.7%, >80% reduction highlighted (control=100%)

Conclusions

All weed species investigated showed that exposure to heat could provide control of seeds, but there were large differences between weeds in their tolerance to heat. Combinations of high temperature and exposure time investigated could provide complete kill of all species except marshmallow. High temperature and duration of burn expected from burning narrow windrows should provide effective seed kill of most of these species. However, the performance of this method is completely dependent on how much of the weed seeds can be collected at harvest (HWSC) and placed into narrow harvest windrows. Grass weeds all showed similar patterns of tolerance to heat with ARG being the most tolerant. Despite the higher tolerance to heat, high pre-harvest seed retention in ARG makes it more suited to effective control from residue burning (narrow windrows) than barley grass which sheds most of its seeds well before harvest. Among brassica weeds, IHM showed good potential for control by burning harvest windrows as it is sensitive to heat and HWSC methods.

Acknowledgements
The author would like to acknowledge the South Australian Grains Industry Trust for funding this research as part of the S416 – Burning of weed seeds in low rainfall farming systems project. Ruth and Damien Sommerville, Barry Mudge, Amanda Cook and Ian Richter for their involvement in seed collection. Rochelle Wheaten and Brett Hay for their involvement in packing seed. Daniel Petersen, Malinee Thongmee and Jerome Martin for their involvement in assessment. Hugh Cameron for involvement in setting up kiln and with seed racks. Naomi Scholz for managing the S416 project.

References

Fleet B, Thongmee M, Preston C and Gill G (2014) Potential of harvest seed collection of annual ryegrass in the southern cropping region – UA00134. Report for GRDC. University of Adelaide, South Australia.

Fleet B and Gill G (2012) Seed Dormancy and Seedling Recruitment in Smooth Barley (*Hordeum murinum* ssp. *glaucum*) Populations in Southern Australia. *Weed Sci.* 60, 394-400.

Fleet B, Preston C and Gill G (2016) Does windrowing faba beans reduce seed set of Indian Hedge Mustard? - UA0049. Report for GRDC. University of Adelaide, South Australia.

Gill GS and Holmes JE (1997) Efficacy of Cultural Control Methods for Combating Herbicide-Resistant *Lolium rigidum*. *Pestic. Sci.* 51, 352-358

Kleemann S, Martin J and Gill G (2016) Seedbank Biology of Emerging Weeds in the Southern Region – UA00156. Report for GRDC. University of Adelaide, South Australia.

Llewellyn RS, Ronning D, Ouzman J, Walker S, Mayfield A and Clarke M (2016) *Impact of Weeds on Australian Grain Production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices* Report for GRDC. CSIRO, Australia.

Pitt JL, Vitrue JG and Feuerherdt LJ (2006) *Onion weed: Pest or perception. In Managing weeds in a changing climate: Australian weeds conference, 15th, 24-28 Sep 2006, Adelaide SA, eds Preston C, Watts JH and Crossman ND*, 454-457. Weed Management Society of South Australia, Adelaide SA.

Shergill L, Fleet B, Preston P and Gill G (2015) Incidence of Herbicide Resistance, Seedling Emergence, and Seed Persistence of Smooth Barley (*Hordeum glaucum*) in South Australia. *Weed Tech.* 29, 782-792.

Walsh M and Newman P (2007) Burning of narrow windrows for weed seed destruction. *Field Crops Research* 104, 24-30.