Evaluating canopy reflectance for assessment of frost damage in wheat

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Abstract
Frost has the potential to significantly reduce production for field crops grown in Mediterranean-type environments, and significant economic losses due to frost damage for Australian wheat occur annually. If non-destructive sensors could make rapid, spatial assessment of frost damage near heading and anthesis, this could limit losses through timely management decisions. For this research we analysed canopy reflectance measurements as part of a field experiment in 2016 at Horsham. Mobile frost chambers applied chilled air (temperatures below 0°C) to wheat at heading and anthesis, and repeated canopy reflectance measurements were made following the treatments at leaf, head, and canopy scales. The reflectance measurements were used to determine a suite of reflectance indices, which were compared with frost intensity expressed as cold sums. Many of the indices demonstrated significant, linear relationships with frost intensity for heading treatments that were in excess of 20 °C.hr<0 (or minimum temperatures of -6.6 to -9.6°C). Immediately following the anthesis frost treatments (with frost intensities < 20 °C.hr and minimum temperatures of -0.7 to -4.2°C), only two indices, Photochemical Response Index (PRI) and Plant Senscence Reflectance Index (PSRI), showed significant relationships, and only for flag leaves. Eight days following anthesis treatments, six indices resulted in significant R^2 values, although the values were lower than for the heading treatment. Initial results indicate that research should target frost intensities equivalent to cold sums between 20 and 50 °C.hr, to better understand at what point reflectance (and other non-destructive measurements) can detect frost damage.

Keywords
Remote sensing, hyperspectral reflectance, drones, unmanned aerial vehicles.

Introduction
For field crops grown in Mediterranean-type environments, frost has the potential to significantly reduce production (Zheng et al. 2015). Economic losses due to frost damage for Australian wheat have been estimated up to $100 million per year (Juttner 2014). If non-destructive sensors could make rapid, spatial assessment of frost damage near heading and anthesis, this could limit losses through timely management decisions on whether to continue growing the crop for grain or cut portions (or all) of a field for hay. Potential sources of non-destructive data for frost assessment include leaf/canopy reflectance, chlorophyll fluorescence, and radiometric surface temperatures. Reflectance measurements have the advantage of offering a range of potential sensors (e.g., multispectral imaging cameras, active optical crop sensors, and customised pocket instruments), platforms (handheld, unmanned aerial vehicles (UAVs), satellites) and scales (from individual leaves to satellite imagery capable of covering regions). In this paper we focus on an assessment of canopy reflectance for early detection of frost damage. We are presenting initial results for research into the use of reflectance measurements for frost damage assessment, including how early damage can be detected, at what scales, and what are the critical reflectance wavelengths that are required.

Methods
Canopy reflectance measurements were undertaken as part of a field experiment in 2016 at Horsham, Australia to examine the impact of simulated frost on wheat production. This experiment is described in more detail in Nuttall et al. (2017). Eleven treatments were applied to four reps, totalling 44 plots. Mobile frost chambers applied chilled air (temperatures below 0°C) to wheat at heading (H) and anthesis (A). At heading three different cold scenarios were applied to wheat (*cv*. Yitpi) where for treatments H#1, H#2 and H#3, treatments were applied over 1, 2 and 3 consecutive nights within the time period 21/10 to 23/10. At anthesis, six different cold scenarios were applied; a first set of three (treatments A1 to A3) frost treatments

were applied over a single night (31/10/16) with increasing intensity of chilling and a second set of treatments (treatments A4 to A6) which were applied over two consecutive nights (01/11/16 & 02/11/16), also with increasing intensity. Canopy temperatures were monitored using thermocouples installed at canopy (head) height, and temperature was logged at five minute intervals using TGP-4505 external temperature and relative humidity probes. The level of frost exposure was determined by integrating the time over which canopy temperatures were below 0°C, expressed as °C.h (< 0°C). It should be noted that the frost treatments applied at heading were severe and resulted in damage that was visible the next day, while the anthesis applications, designed to be more subtle, were not visible.

Canopy reflectance was measured using a handheld spectroradiometer (ASD Field Spec FR, Boulder CO USA) and a six band multispectral camera (Tetracam Micro-MCA Chatsworth CA, USA) following frost treatments. Spectroradiometer measurements were made on 24/10 (the day following the last heading treatment, on 3/11 (the day following the last anthesis treatment), and 11/11. On 24/10 and 3/11, measurements were made at canopy and leaf scales. Five spectra for each plot were acquired at 0.1m above the top of canopy (0.04 m sample diameter) and three spectra at 0.4 m above the canopy (0.18 m sample diameter). A leaf clamp with internal illumination was also used to five spectra each for the leaf and head components separately per plot. On 11/11 five canopy level measurements (per plot) were made 0.15 m above the canopy, resulting in 0.07m sample diameter. On all dates the spectroradiometer measurements were normalised to reflectance using a Teflon™ or Spectralon™ calibration reference. Canopy reflectance was also acquired with a multispectral camera flown on a multi-rotor UAV on 3/11. The camera is configured with six 10 nm wide spectral bands at 550 nm, 660 nm, 710 nm, 720 nm, 730 nm and 810 nm. Imagery was acquired at multiple elevations, for this paper an image acquired at 55 m above ground was used, resulting in 0.02m pixel resolution. The imagery was corrected to reflectance using calibration panels placed in the experiment at canopy level. The reflectance spectra from the spectralradiometer and the multispectral camera were used to compute indices listed in Table 1. For each of the 44 plots, each spectrum from the spectroradiometer was used to compute an index value, and the mean index value was used to represent that plot. For the multispectral camera, the pixels representing each of the 44 plots were averaged by band to generate one index value per plot. This was to compensate for any pixel mis-alignment between the spectral bands in the imagery.

Table 1. Spectral indices computed from reflectance measurements.

Index	Formula	Reference
Canopy Chlorophyll Concentration Index (CCCI)	Based on NDVI and NDRE, below	Fitzgerald et al. (2010)
(Modified) Cellulose Absorption Index, CAI	0.5(R2.0 + R2.2) - R2.1	Daughtry (2001)
Chlorophyll Index Red-edge, CI	(RNIR/NRE)-1	Gitelson et al. (2006)
Enhanced Vegetation Index, EVI	G*(NIR-R)/(NIR+6*R-7.5*B + 1)	Huete et al. (2002)
Modified Chlorophyll Absorption Reflectance Index, MCARI	((R700-R670)-0.2*(R700-R550))*(R700/R670)	Daughtry et al. (2000)
Normalised Difference Red-Edge Index, NDRE	(R800-R720)/(R800+R720)	Clark et al. (2001)
Normalised Difference Vegetation Index, NDVI	(R800-R670)/(R800+R670)	Rouse et al. (1973)
Photochemical Response Index, PRI	(R570-R531)/(R570+R531)	Gamon et al. (1992)
Plant Senescence Reflectance Index, PSRI	(R680 - R500)/R750	Merzlyak et al. (1999)
Structure Insensitive Pigment Index, SIPI	(R800-R445)/(R800-R680)	Peñuelas et al. (1995)
Triangular Greenness Index	-0.5*((670-480)*(R670-R550)-(670-550)*(R670-R480))	Hunt et al. (2013)
Water Index, WI	R900/R970	Peñuelas et al. (1997)

Results and Discussion

For the current analysis, the frost exclusion chamber plots were excluded as the phenology of the wheat in the exclusion chambers was effected. The open air control plots were used as they were not exposed to any natural frost episodes during the anthesis phase. Cold sum values for each plot were regressed on each of the indices from Table 1, for each of the measurement dates (Table 2). For the heading frost treatments, the cold sums ranged from 0 (control plots) to 174 °C.hr <0, and minimum temperatures of frost treatments ranged from -6.6 to -9.6°C. Several of the indices evaluated resulted in a significant, linear response for the 0.1m and 0.4 m above canopy measurements, as well as the flag leaf measurements. The reflectance measurements for the individual heads resulted in generally lower R^2 values. The maximum cold sums for the anthesis treatments (19 °C.hr <0) was far less than for the heading treatment, and the minimum canopy temperatures ranged from -0.7 to -4.2°C. The plants showed no visual signs of frost damage following the treatments (Nuttall et al. 2017). For anthesis treatments, the only significant regression models were based on measurements for PRI and PSRI for the flag leaves. The indices computed from the UAV measurements showed little response of the indices to the cold treatments. For reflectance spectra (11/11) on the heading treatments, regression of cold sums on the indices resulted in six indices (MCARI, NDVI, PRI, PSRI, SIPI and Mod-CAI) with R^2 values being significant at Pr <0.05 or better, although the R^2 values were lower than for the heading treatment.

The index PRI is plotted against frost treatment intensity in Figure 1. The linear response to cold sums can be seen for the full range of heading treatments (Figure 1a). The variability seen in the anthesis treatments (Figure 1b) indicates that it may be difficult to establish relationships without including higher frost intensities. However, the anthesis measurements appear to fit the overall trend of the full range. The index values for the wheat head measurements are different than the flag leaf and canopy measurements, while the values for the flag leaf measurements were similar to the canopy level measurements.

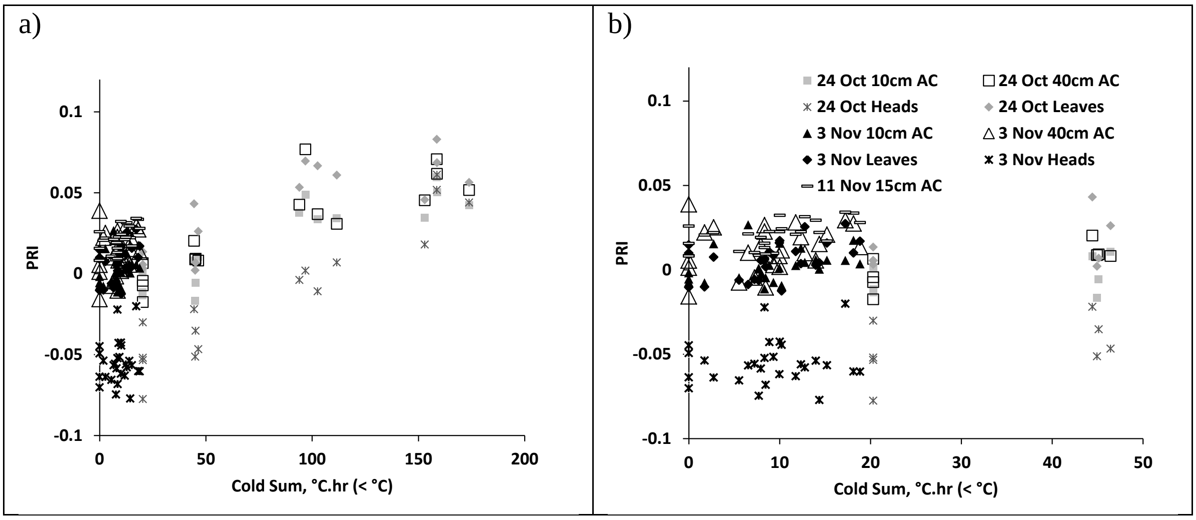

Figure 1. Response of the spectral index PRI to canopy frost exposure for a) full range of heading and anthesis treatments, and b) anthesis measurements only.

Table 2. Regression results for frost intensity (by cold sums) as a function of reflectance indices.

Measurements	*CCCI*	*CI*	*EVI*	*MCARI*	*NDRE*	*NDVI*
24 Oct 10cm Above Canopy	0	29.2*	12.7	50.2***	66.5***	81.3***
24 Oct 40cm Above Canopy	0	26.6*	18.8*	54.8***	62.0***	75.0***
24 Oct Leaves	36.2**	33.0*	11.7*	56.5***	55.2***	64.3***
24 Oct Heads	10.1	02.8	0	29.8*	35.1**	55.6***
3 Nov 10cm Above Canopy	0	0	0	1.8	0	1.1
3 Nov 40cm Above Canopy	0	0	1.1	0	0	0
3 Nov Leaves	0	5.6	0	0	10.6	4.5
3 Nov Heads	8.0	0	1.3	4.4	0.9	0
3 Nov UAV	0	0		0	0	0
11 Nov 15 cm Above Canopy	0	0	0	19.8*	2.8	19.0*
Measurements	***PRI***	***PSRI***	***SIPI***	***TGI***	***WI***	***Mod_CAI***
24 Oct 10cm Above Canopy	79.4***	74.3***	74.0***	23.9*	60.9***	4.4
24 Oct 40cm Above Canopy	73.4***	71.3***	71.1***	41.0**	52.2***	25.7*
24 Oct Leaves	68.7***	59.4***	52.1***	25.3*	57.5***	0
24 Oct Heads	88.2***	66.8***	59.4***	0	56.3***	4.6
3 Nov 10cm Above Canopy	3.0	1.6	2.0	0	0	0
3 Nov 40cm Above Canopy	2.8	0	0	0	0	0
3 Nov Leaves	14.8*	11.9*	9.4	0	2.1	0
3 Nov Heads	0	0	0	4.1	0	0
3 Nov UAV		6.4				
11 Nov 15 cm Above Canopy	29.4**	25.7**	22.6**	03.9	0	17.7*

*Pr<0.05; **Pr<0.01; ***Pr<0.001

Conclusions

Many of the indices demonstrated significant, linear relationships with frost intensity for treatments that were in excess of 20 °C.hr<0 (or minimum temps of -6.6 to -9.6°C). Generally there was no relationship for anthesis treatments with frost intensities < 20 °C.hr immediately following the treatments for reflectance measurements of the canopy, flag leaves, or heads. However, two indices, PRI and PSRI, showed significant (Pr<0.05) relationships with cold sums, based on measurements made on flag leaves. Eight days following the anthesis treatments, some indices appear to relate to frost intensity based on canopy reflectance measurements. These initial results indicate that research should target frost intensities equivalent to cold sums between 20 °C.hr and 50 °C.hr, to better understand at what point reflectance (and other non-destructive measurements) can detect frost damage. Three of the indices evaluated (PRI, PSRI and SIPI), while showing some indication of use for frost detection, cannot be measured by the multispectral camera in the current configuration. However, other narrow band filters could be implemented to allow the computation of these indices.

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