Matching radiation characteristics with crop architecture to maximise radiation-use efficiency in the High Rainfall Zone

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Abstract

Diffuse radiation is more effective at penetrating into thick crop canopies than direct radiation, leading to a higher radiation use efficiency. To quantify the fraction of diffuse radiation in Australia's high rainfall zone, a sensor that distinguishes between diffuse and global (diffuse + direct) radiation was used at Hamilton for the 2016 growing season. Monthly means from these measurements were highly correlated ($R^2 = 0.99$) with values derived by a surrogate that uses daily radiation from the SILO database. Using the surrogate, diffuse radiation accounted for 62% of global radiation at Hamilton between June and October, which is the core of the growing period. Across other sites in the high rainfall zone, diffuse radiation during this period ranged from 49% at Canberra to 61% at Cressy (Tasmania) and Lake Bolac (Victoria). Given the high proportion of diffuse radiation during the growing season in the high rainfall zone, it is proposed that the ideal crop architecture is planophile (flat leaves) as a seedling, followed by erectophile (erect leaves) as the canopy develops.

Keywords

Planophile, erectophile, ideotype, SILO.

Introduction

Grain crops in Australia's high rainfall cropping zone (HRZ) face potential light limitations during dull days during winter and early spring . One strategy to intercept more light early in the crop's development is to plant crops in an east west orientation, so the shadow falls on the inter-row area during most of the day. In a series of studies at Merredin in Western Australia, Borger et al. (2010; 2015) found that east-west rows produced higher yields and suffered less weed competition than north-south rows, because of greater light interception by the crop. However, this strategy is only likely to be successful if direct radiation forms a high proportion of the total. As the canopy develops, diffuse light is more effective at penetrating into the crop than direct light, because direct light creates strong shadows on leaves deeper within the canopy (Li and Yang 2015). In a meta-analysis of wheat and barley yields, Rodriguez and Sadras (2007) found strong positive relationships between the fraction of diffuse radiation (FDR) and both radiation use efficiency and water use efficiency. In the HRZ under a heavy canopy and high FDR, an erect crop architecture would be expected to enable deeper penetration of diffuse light into the canopy than a planophile architecture. We therefore expect that understanding the solar radiation environment is a key to developing successful agronomic practices and crop ideotypes for maximising radiation use efficiency by crops.

In the study of Rodriguez and Sadras (2007), diffuse radiation was calculated from daily global radiation using a relationship of Spitters et al. (1986), which had been derived from measurements reported between 1960 and 1982. Global radiation was sourced from the SILO database (Jeffrey et al. 2001), which uses satellite observations (Zajaczkowski et al. 2013). While this combination of surrogates was useful in their study, it would be useful to compare the surrogates with direct measurement of FDR given recent advances in measurement equipment.

The aims of this study were (i) quantify FDR and solar angles during the 2016 growing season, (ii) compare direct measurement of FDR with estimates from daily solar radiation from SILO and an on-site weather station using the relationship of Spitters et al. (1986), and (iii) quantify FDR at representative sites in the HRZ.

Methods

Measurements

In May 2016 a sensor (SPN1, Delta T Devices, Cambridge, UK; SKU430, Skye Instruments, Llandrindod, Wales) that distinguishes between diffuse and global (diffuse + direct) solar radiation was installed adjacent to a wheat architecture trial and data were logged at 10 minute intervals. The sensor was close to the weather station of the Hamilton Research Station, which records daily global radiation (Monitor Sensors, Caboolture, Queensland). Daily global radiation data was also obtained from the SILO database (Jeffrey et al. 2001) for the period 2000 to 2017 for the Hamilton Research Station (-37.83°), Cressy, Tasmania (-38.03°), Kojonup, Western Australia (-33.83°), Canberra, ACT (-35.30°) and Lake Bolac (-37.71°). As a comparison from a low-rainfall cropping zone, Merredin (-31.48°) was included because of the prior studies that had been undertaken on row orientation. Solar angle and extra-terrestrial radiation were estimated by the FAO56 equations (Allen et al. 1998) at 10-minute and daily time-steps. The relationship of Spitters et al. (1986) was used to calculate FDR from extra-terrestrial radiation and daily global radiation.

Results

Solar angles: The solar angle calculated for the winter solstice (22 June) at Hamilton ranged from 72° from vertical at 10:00 to a minimum of 61° at 12:40 (Figure 1a). At these angles, a row of young wheat plants 10 cm high in east-west rows would cast a shadow 23 cm into the inter-row area at 10:00, while at 12:40 the shadow length would be 18 cm. At the equinox (22 September), the corresponding angles were 50° and 37° respectively.

Diffuse radiation: Maximum crop growth rate in the adjacent wheat architecture trial occurred between 1 and 14 October, which corresponded to the period between wheat booting and anthesis. During this period, there were five days when direct radiation exceeded 50% of global radiation. On a clear day during this period (8 October), diffuse radiation averaged 119 W/m^2 between 9:00 and 15:00, whereas on a cloudy day (9 October) the corresponding average was 313 W/m^2 (Figs 1 b and c). On these days, FDR was 0.20 and 0.83 respectively, and global radiation 26 and 11 MJ/m^2/d.

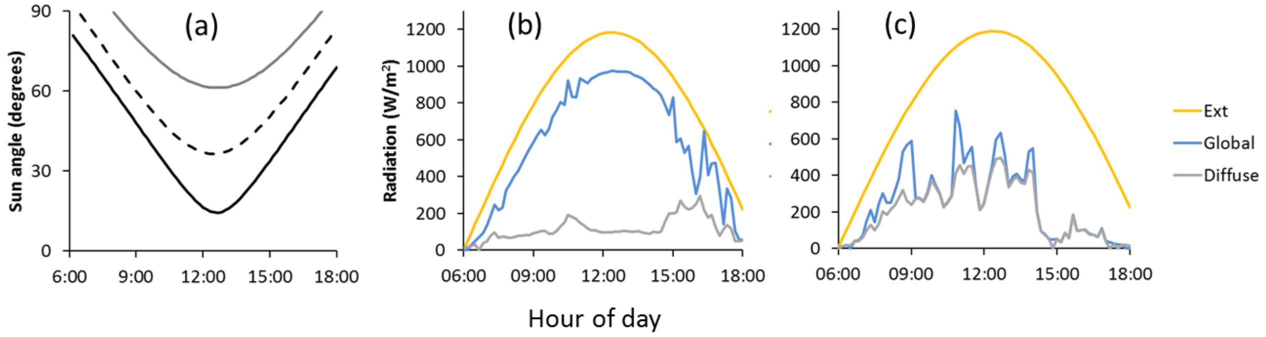

Figure 1. (a) Sun angle for direct solar radiation at Hamilton at the winter solstice (grey line), equinox (dashed line) and summer solstice (solid black line). (b) Diffuse, global and extra-terrestrial radiation for a clear day (8 October 2016) and (c) a cloudy day (9 October 2016).

FDR: The relationship between FDR and global radiation followed that of Spitters et al. (1986) with a root mean square error of 0.085 (Figure 2a). Monthly mean measured FDR was highly correlated with both the Spitters-SILO surrogate, and the Spitters relationship used with data from the Hamilton weather station (R^2 = 0.99 and 0.88 respectively) (Figure 2b). However, measured FDR averaged 16% lower than both surrogates. Across sites in the HRZ, diffuse radiation from Spitters-SILO comprised more than half the global radiation during the main part of the growing season between June to October at all sites except Canberra (Figure 3). The highest FDR during this period was at Hamilton (0.62) followed by Cressy (0.61), Kojonup (0.55) and Canberra (0.49). Lake Bolac (0.61) was similar to Cressy (not shown on Figure 3 for clarity). Canberra had three peaks of FDR in February, June and November, while all other stations had a single peak in June or July. Merredin (0.45) had much lower FDR than most of the HRZ stations. In July, when row orientation would be expected to have the greatest effect on light interception by the crop, FDR ranged from 0.49 at Merredin to 0.66 at Hamilton.

Discussion

Diffuse radiation dominates the radiation environment in the HRZ, comprising more than half of global radiation at all sites except Canberra. For seedlings growing in east-west rows, shadowing of the inter-row area is only relevant for the direct component of the radiation, which in July ranges from 51% at Merredin to 34% at Hamilton. The diffuse component of radiation not intercepted by the crop would fall on the inter-row area, being lost to the crop but available for competing weeds. In the HRZ with its high FDR, there would be limited gains from optimising row orientation, and the ideal architecture at this time of crop development would be planophile, to occupy ground area and smother weed competition. This hypothesis is supported by studies in Western Australia, which have shown that the greatest benefit of east-west over north-south rows is with erect rather than planophile crop species, and in drier areas that would have a lower FDR (Borger et al. 2010, 2015).

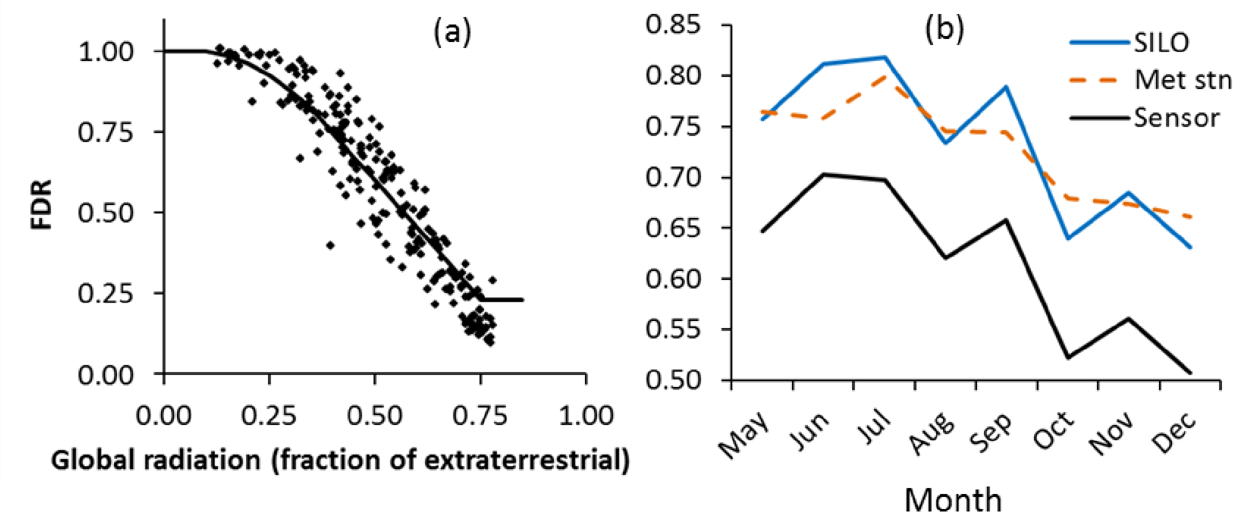

Figure 2. (a) Relationship between the daily fraction of diffuse radiation (FDR), and global radiation as a percentage of extra-terrestrial at Hamilton May 2016 to January 2017 (points), and the relationship of Spitters et al. (1986) (line). (b) FDR averaged for each month at Hamilton May-December 2016 calculated from the SPN1 sensor, and calculated from daily solar radiation from SILO and the weather station at the Hamilton Research Station using the relationship of Spitters et al. (1986).

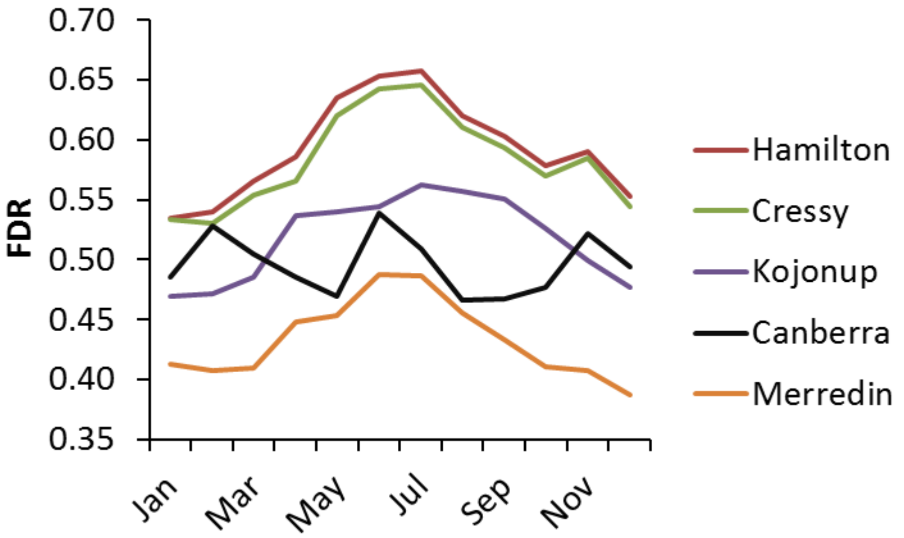

Figure 3. The fraction of diffuse radiation (FDR) averaged for each month between 2000 and 2016 calculated by the Spitters-SILO surrogate for several locations in the high rainfall cropping zone, and Merredin as a representative of the low rainfall zone.

At maximum crop growth rate, in October, the high FDR in the HRZ means that there is greater scope to facilitate solar radiation penetrating deep into the canopy using erect plants than there would in drier,=more northern areas, where the high proportion of direct radiation would cause stronger shadowing within the canopy. Optimal plant architecture for the HRZ therefore appears to be planophile as a seedling, followed by erectophile as the canopy develops. Barley and capeweed are two examples of such plants.

Measured FDR was consistently lower than the Spitters-weather station and Spitters-SILO surrogates, but the methods were highly correlated. The high correlation means that the surrogates can be applied confidently, but must be compared with other values derived by the same method. Resolving the cause of differences between the methods would require detailed attention to calibration between equipment types, and detection tolerances. For example, the SPN1 sensor used here often did not detect radiation below 50 W/m^2, leading to a portion of the daily total not being included. This feature was only detected because of 10-minute logging, and a similar comparison would need to be undertaken with other equipment types.

Conclusion

Diffuse light accounts for over 50% of global radiation during the growing season across most of Australia's HRZ. Measurements of FDR taken during this study were highly correlated with an algorithm that used daily solar radiation data from the SILO database. These data are sourced from satellites and are readily available to crop modellers. To utilise the resource of diffuse radiation in the HRZ, we propose that the optimal plant architecture is planophile at the seedling stage, followed by erectophile as the canopy develops.

Acknowledgements

We thank GRDC for supporting this study through DAV000141, and for co-investment support from the Victorian Department of Economic Development, Jobs, Transport and Resources, and the CSIRO.

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