Modification to the French and Shultz formula to account for soil type and within-season rainfall.

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Abstract

We have modified the French and Shultz (1984) equation (FS) that estimates water-limited yield potential to account for soil plant available water capacity (PAWC), stored soil water at sowing and the gross amount of seasonal rainfall. This modified FS, called PAR_m, is a spreadsheet model which uses a monthly time-step that sums the rainfall that can enter a soil profile based on the PAWC and the stored soil water once potential evapo-transpiration has been removed. A farmer friendly adaptation, the PAR_{GSR} uses only whole of growing season rainfall and PAWC.

The yield potential estimated by FS, PAR_m and PAR_{GSR} models were compared using 148 measured wheat yields (400-5200 kg/ha) from the wheatbelt of WA. The error (RMSE) in yield prediction was improved from 1560 kg/ha with FS, to 670 kg/ha with the PAR_m model and 850 kg/ha with the PAR_{GSR} model compared to 530 kg/ha using the crop simulation model APSIM.

Key words

Yield potential, plant available water capacity, wheat, model, water use efficiency

Introduction

Rainfall is the main driver of yield potential in the dryland cropping environment of Australia and, hence, rainfall-based models like French and Shultz (FS) can be used to determine an upper limit of yield potential (French and Shultz 1984). Many farmers and advisors are still using FS to estimate yield but it often overestimates yield as it does not account for rainfall distribution, runoff, drainage or access to stored soil water (Robertson and Kirkegaard, 2005). Farmers deny themselves the opportunity to more accurately estimate yield potential because they do not wish to or cannot simply access complicated and data-hungry models such as APSIM or Yield Prophet[?]. Here we describe a simple model that can be used by farmers to predict yield with close to the accuracy of more complex models such as APSIM.

Methods

Measured wheat yields for 148 dryland crops, managed to water limited yield potential, covering the 1997 to 2006 seasons, were obtained from published literature (Oliver et al. 2006, 2008) and unpublished data from the WA wheatbelt (Mingenew, Buntine, Kellerberrin, Esperance, Dumbleyung, Corrigin). Yields ranged from 400 to 5200 kg/ha (2330 kg/ha average) and and growing season rainfall 103 to 439 mm (251mm average). For each crop, the information available included: soil type, soil PAWC, closest rainfall station or monthly farmer-measured rainfall, measured yield, most agronomic information required for APSIM, and APSIM simulated yield.

FS and FS adaptations

The French and Shultz equation (1984) was developed to determine the upper limit of yield potential based on growing season rainfall. Common adaptations of FS include the addition of stored soil water or the adjustment of the water use efficiency (WUE) term.

$$YP_{FS} = (GSR + S_A - I) \times WUE \quad (1)$$

Where YP_{FS} = Yield potential estimated by the FS equation (kg/ha), GSR = growing season rainfall (mm) which in WA is considered to be May to Sept or Oct. S_A = Stored water at the start of the season which can be measured or estimated at 25% to 30% of summer rainfall (Dec and April) or is zero in the original FS. I = the intercept which is the threshold rainfall required before a crop will grow, commonly 110 mm; it can also be adjusted to account for a lower intercept at lower GSR. WUE = water use efficiency for grain production of the crop which is 20 kg/ha/mm, but can be adjusted for soil type or can be calculated from historic paddock yields and rainfall.

Plant available rainfall to estimate yield potential (PAR_m) model

We have created a new model we call Plant Available Rainfall (PAR_m) which is based on FS but uses monthly rainfall data (or a monthly time-step) to adjust the growing season rainfall based on the soils PAWC or "bucket". It assumes not all rainfall can enter a soil bucket due to runoff or that the water may not be accessible for a crop as it has moved below the root zone.

The maximum rainfall allowed into the bucket each month (RFB_A) is determined from the PAWC, the amount of water in the soil (S_A) and the amount lost via potential evapo-transpiration in that month (ET_A) (Eq. 2).

$$RFB_A = PAWC + ET_A - S_A \quad (2)$$

Where A = start of growing season month to last month of growing season, A+z, S_A can range from zero to PAWC and ET for each month was estimated from an average APSIM value modelled using a range of soils, 100 years of climate data from a number of sites in the northern, central and eastern wheatbelt of WA (data not shown).

The rainfall that can contribute to yield, RFY_A, depends on whether the monthly rainfall (RF_A) is greater or less than the maximum allowed in the bucket, RFB_A (Eqs. 3a,b)

$$RFY_A = RFB_A \quad \text{when } RF_A > RFB_A \quad (3a)$$

$$RFY_A = RF_A \quad \text{when } RF_A < RFB_A \quad (3b)$$

The stored water at start of the next month (A+1) is calculated from Eq. 4 so that the RFY_{A+1} is determined by following Eqs. 2 to 3

$$S_{A+1} = RFY_A + S_A - ET_A \quad (4)$$

The rainfall which contributes to yield over the growing season (RFY_{GSR}) is the sum of the monthly RFY (Eq. 5). This is then used to calculate the yield potential (YP_{PARm}) (Eq. 6) using a WUE of 20 kg grain/ha/mm, and two intercept values of 130 if GSR > 180 mm, or 90 if GSR < 180 mm where these intercept values were selected by trial and error and remain to be justified by more objective means.

$$RFY_{GSR} = RFY_A + RFY_{A+1} + \ldots RFY_{A+z} \quad (5)$$

$$YP_{PARm} = (S_A + RFY_{GSR} - I) * WUE \quad (6)$$

Simplifying the PAR model

We have also developed an even simpler model for direct farmer use, PAR_{GSR}, which uses only whole of growing season rainfall and soil PAWC. By plotting the GSR versus the rainfall which contributes to yield from the PAR_m model (Fig. 1) we found that below a threshold of GSR the FS is a good estimate of yield potential, and suggest use of Eq. 1. Above this threshold, extra rainfall cannot contribute to yield, so the threshold value is used to estimate yield potential (Eq. 7); the threshold values vary with PAWC (Table 1).

$$YP_{PARGSR} = (threshold + S_A - I) \times WUE \qquad \text{when } GSR > threshold \qquad (7)$$

Table 1. Threshold values for rainfall when the PAWC is between 40 and 150 mm.

PAWC (mm)	Rainfall threshold (mm)
40	220
50	230
60	240
70	250
80	265
90	275
100	285
150	345

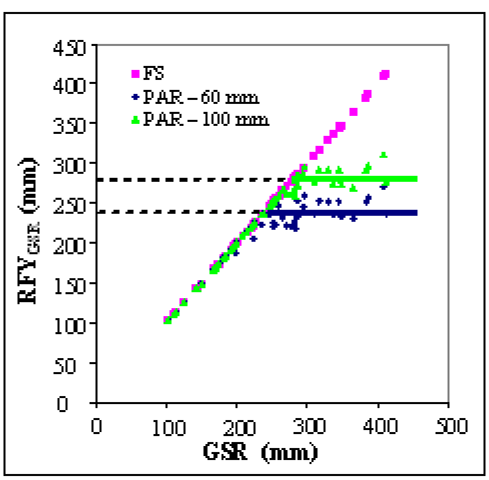

Fig 1. Relationship between GSR and RFY_{GSR} from the PAR-YP model for a PAWC of 60 mm and 100mm

Results and Discussion

FS overestimated measured yields particularly at “high” rainfall (GSR >240mm) and underestimated yield at low rainfall (GSR < 240 mm) (Fig 2), with a high RMSE 1561 kg/ha and low r^2 (0.188) (Table 2). Overestimation could be caused by drainage below the root zone or runoff, whereas underestimation may be caused by not including stored water or using an intercept value that is too high.

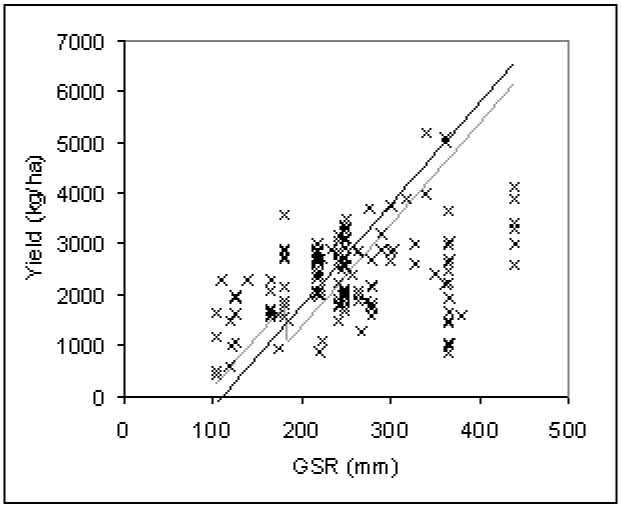

Fig 2. The GSR (mm) versus measured yield (kg/ha) (x) and yield estimated from FS (—) and FS (—) with 2 values of A (Eq. 1).

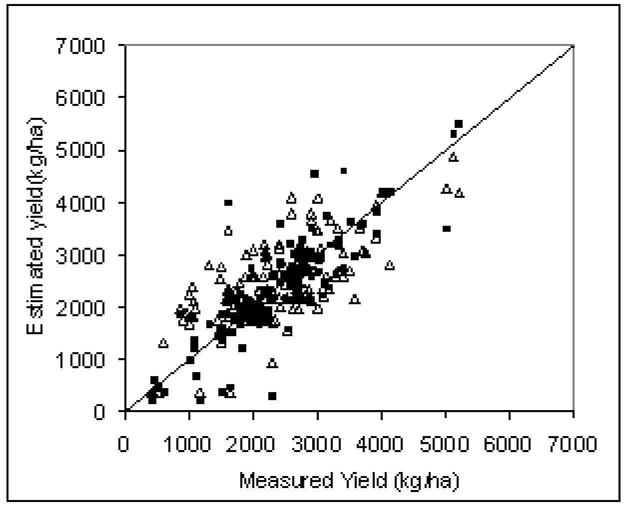

Fig 3. Comparison of the measured yield and estimated yield for PAR-YP which uses 2 values of A and SA (∆) and the APSIM (●).

Table 2. Error of prediction in yield (RMSE) and scatter (r^2) for the different methods and inclusion of differing water-use intercept (I) and stored soil water (S_A).

Method	Inclusions	RMSE	R^2
FS		1561	0.188
FS :	two I values	1357	0.168
FS :	two I values and S_A	1737	0.109
PAR_m	two I values	744	0.480
PAR_m	two I values and S_A	667	0.446
PAR_{GSR}	two I values	754	0.308
PAR_{GSR}	two I values and S_A	851	0.442

APSIM	528	0.729

Adjusting the intercept in the FS model reduced the amount of under-prediction at GSR < 240 mm and reduced the over-prediction at GSR > 240 mm (Fig 2, 3), however this did not improve the ability of FS to predict yield (Table 2). The inclusion of stored soil water generally reduced the under-prediction of yield in lower rainfall (< 240 mm) but often increased the predicted yield at high rainfall (> 240mm), which was often already over predicted, thus increasing the error (RMSE) in predicting yield (Table 2)

By accounting for rainfall distribution and soil PAWC, the PAR_m model almost halved the error in prediction of yield compared to FS (Table 2, Fig 3). The PAR_m model can be used with either 1 or 2 values of intercept (I), and with and without stored water, however the inclusion of stored water increased the prediction accuracy of the PAR_m model (Table 2). Using a standard WUE of 20 kg grain/ha/mm enabled the PAR_m model to estimate yield potential based on soil type and rainfall distribution, thereby eliminating the common practise of adjusting the WUE, either for soil or historic paddock average.

The PAR_m model requires use of a computer spreadsheet, which may limit its use by farmers and consultants. Simplification of the PAR_m model to the PAR_{GSR} so that it was "farmer friendly" reduced the ability to predict yield compared to the PAR_m model, but was still significantly better at predicting yield than FS (Table 2).

A more complex model like APSIM was able to predict yield with a smaller error (RMSE) of 530 kg/ha and had a smaller scatter (r^2=0.74) (Table 2, Fig 3). Models like APSIM (Keating et al. 2003) and Yield Prophet?, however, require much more detailed soil and agronomic information than that required by simple models such as FS or the PAR models presented here. When used with accurate and specific site-derived data, Yield Prophet predicts yield within 0.5 t/ha in 68% of simulations but this decreased to 49% of simulations when estimates of soil properties are used (Hunt et al. 2006). For the majority of cases, therefore, where a simple estimate of yield potential is required in the absence of highly detailed soil and agronomic data, the modified FS models presented here, PAR_m and PAR_{GSR}, provide a comparably accurate and reliable estimate of yield potential.

Conclusions

The PAR_m spreadsheet model is able to account for soil type and stored water but still uses a simple equation based on FS. It predicted yield with about half the error of FS (667 cf. 1561 kg/ha). A simplified version of this model, PAR_{GSR} improved the prediction of yield in the higher rainfall years with an error of 850 kg/ha. This simplified version is "farmer friendly" and yield can be calculated on "the back on the envelope" provided GSR and estimate of PAWC is known.

A spreadsheet version is available from the author.

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