A simple N calculator for achieving water-limited yield of wheat crops

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Abstract

The increasingly chaotic nature of rainfall challenges growers to balance nitrogen fertiliser inputs for both production and environmental imperatives. Too little nitrogen restricts yields and runs down soil organic carbon, while too much nitrogen is economically wasteful and environmentally harmful. We investigated two comprehensive Australia-wide data sets, one from commercial wheat growers' fields and the other from systematic simulation of 50 sites by 15 years using APSIM. From these data, we derived a simple non-linear wheat yield model that can be used to calculate the N required to achieve water-limited yield. This model is a departure from the French and Schultz type model and a good mimic of APSIM modelling without the need for detailed parameterisation.

Keywords

Climate variability, evapotranspiration, crop yield, simulation, boundary function

Introduction

The most limiting factors affecting cereal production in rainfed environments are the amount of water (expressed as seasonal evapotranspiration; ET) and nitrogen (N) available. Knowledge of the factors governing supply and demand of N is essential to predict the needs of crops under a wide range of field situations so that growers can be given more reliable fertilizer recommendations. This is important as risks to the environment can arise from the over-application of N fertilizers while under-fertilization causes soil degradation and low yields and is the most important single factor explaining large yield gaps in Australia (Hochman and Horan 2018). There is no shortage of studies of ET and N effects on wheat yields. However, these have usually produced N response functions at specific levels of ET supply, or ET response functions at specific levels of N, for a single or a few seasons and/or locations with limited applicability to other environments.

APSIM (Holzworth et al. 2014) and similar process-based models can simulate crop growth and yield in response to limited ET and available N and may be used to simulate yields under a wide range of N and water supply conditions by capturing key aspects of the interactions between water and nitrogen. The APSIM wheat model has been evaluated in numerous publications, especially its grain yield response to a wide range of nitrogen fertiliser applications and water supply conditions (e.g. Keating et al. 2003; Kassie et al. 2016) where nitrogen applications, water supply, and planting dates had large effects on observed biomass and grain yields, and the model reproduced these crop responses well. However, process-based models require a significant amount of parameterization, especially of soil water holding characteristics, soil organic matter, plant available soil water and mineral nitrogen status of the whole profile to the depth of maximum root penetration. This requirement puts the practical application of these models beyond the reach of most grain growers and their advisors. At the opposite end of the complexity scale, there are rules of thumb, whereby target yields are multiplied by a constant value to determine a crop's N requirement. For example, in Yield Prophet Lite a target yield is determined using a simple water use efficiency formula (Sadras and Angus 2006) and this target yield (in t/ha) is then multiplied by 40 to determine the rate of available N (kgN/ha) required to achieve the target yield (http://www.yieldprophet.com.au/yplite/). There do not seem to be any intermediate tools to assist farmers decisions on matching nitrogen fertiliser application to seasonal conditions.

The aim of this research was to establish the optimal rate of N fertilizer to be applied to rainfed crops across a wide range of available soil N and seasonal ET conditions by an investigation of two independent data sets from Australia's cropping zone. The first analysis involves a comprehensive data set of wheat growers' commercial fields, distributed throughout the Australian grain zone over 11 seasons. The second data set consists of simulated yields from 50 sites over 15 years.

Methods

Observed data

The observed data were sourced from the Yield Prophet® data base. It contains grower supplied field level data on grain yield (kg/ha), soil characterization data (including crop lower limit, drained upper limit, bulk density and soil organic carbon) pre-sowing soil mineral N, pre-sowing soil water content, weather data recorded on farm or from the nearest weather station as well as management information including N fertilizer input, time of sowing, crop type and crop variety. The data set includes 960 fields from the years 2005 to 2015. ET was calculated as the sum of in-crop rainfall plus the difference between soil water measured pre-sowing and soil water at harvest. Available N was calculated as the sum of mineral N measured pre-sowing and fertilizer N applied to the crop.

Simulated data

The simulation data used in this analysis are a subset of the simulations produced to investigate the causes of wheat yield gaps in Australia (Hochman and Horan 2018). The Agricultural Production Systems Simulator (APSIM v.7.8; Holzworth et al 2014) was used to model water and N-limited wheat grain yield over the 2001 to 2015 growing seasons using the climate files of 50 sites and soil characterization data representative of the dominant soil type in winter cropping land use within a 20 km radius of the weather station. This spread of sites and years was chosen to ensure that the range of seasonal conditions encountered over the Australian cropping zone is more than adequately captured. In this research we used the same APSIM management rules as those used to simulate water-limited yields except that annual fertilizer N applications were limited to 22.5, 30, 45, and 90 kgN ha-1 in various sites and treatments in order to create a highly diverse set of ET and N-limited situations.

Statistical analysis

The wheat yield response to seasonal ET and Available N was analysed using linear and quadratic regression models, respectively. Individual models were fitted for the observed and simulated data sets. The significance of model parameters was assessed with t tests and their associated P values and the goodness of fit of these models was evaluated with the adjusted coefficient of determination (R^2), which corrects for the degrees of freedom. Boundary functions, at the 95th percentile, were fitted to identify the maximum yield values attainable for given values of ET and Available N for both the observed and simulated data sets. Logistic and quadratic functions were fitted to model the maximum yield response for ET and Available N, respectively. A response surface methodology was followed to identify the appropriate model form of the median yield response to ET and to Available N. Based on the analysis of variance, second-order models with an interaction term were selected because these terms contributed significantly to the model. To minimize bias, median models were calibrated to maximize Lin's concordance correlation coefficient, which measures the relationship between two variables in terms of their deviation from a 1:1 ratio. The significance of each term was assessed using P values for the t test statistic. The prediction accuracy was assessed by computing the R^2 and the Root Mean Square Error (RMSE) between the modelled yields and the observed and simulated yields using a 5-fold cross-validation approach. Multivariate yield frontier models were then developed with Available N and ET as predictor variables. The models had the same functional form as the average models (second order with an interaction term) and were fitted on the 95th percentile of the observed and simulated data sets. For a fuller description of the methods we refer readers to Hochman and Waldner (2020).

Results

For observed data yields averaged 2,667 kg/ha with a range of 140 kg/ha to 7,910 kg/ha. Mean ET across all sites and years was 229 mm with a range from 80 to 526 mm and mean Available N measured across all sites and years was 160 kgN/ha with a range of 25 to 346 kgN/ha. The simulation treatments provided data from 1,814 yield, ET and Available N data sets. Simulated yields averaged

2,725 kg/ha with a range of 200 kg/ha to 7,197 kg/ha. The mean simulated ET across all treatments, sites and years was 212 mm with a range from 59 to 390 mm. The mean simulated Available N across all treatments, sites and years was 139 kgN/ha with a range of 44 to 349 kgN/ha.

Yield as a function of ET

A significant linear correlation of Yield and ET was obtained for both the observed and simulated data sets. The average yield response to total in-crop evapotranspiration (ET) of the observed data was 12 kg grain/mm/ha with a threshold (x-intercept value) of 16 mm while the simulated average yield response to ET was 21 kg grain/mm/ha with a threshold of 81 mm. The relationship between grain yield and ET is commonly described as a boundary function where the boundary is postulated to represent the physiological limit of water use efficiency and water productivity (French and Schultz 1984, Sadras and Angus 2006). Here the best boundary model for both the observed and simulated data sets was found to be a logarithmic function.

Yield as a function of Available N

Grain yields in both the observed and simulated data sets were significantly correlated with Available N. The average response of wheat grain yield to Available N (Yield = f (Available N)) was described as a quadratic function for both the observed and simulated data. The simulated average response curve peaked at 225 kgN/ha with a grain yield of 3,818 kg/ha. The observed response curve was not as steep and peaked at 335 kgN/ha with a similar grain yield of 3,801 kg/ha. The different average responses suggest that, especially with high N supply, observed fields were less responsive to available nitrogen than simulated fields.

Yield as a function of ET and Available N

Grain yields in both the observed and simulated data sets were expressed as polynomial functions with respect to the Available N, ET and an Available N × ET interaction term (Figure 1). All terms of the model were statistically significant (P value < 0.05) in both the observed (Fig 1a) and simulated (Fig 1b) data sets. This combined ET-Available N model accounted for more of the yield variability than either ET or Available N alone for both the observed and simulated data sets.

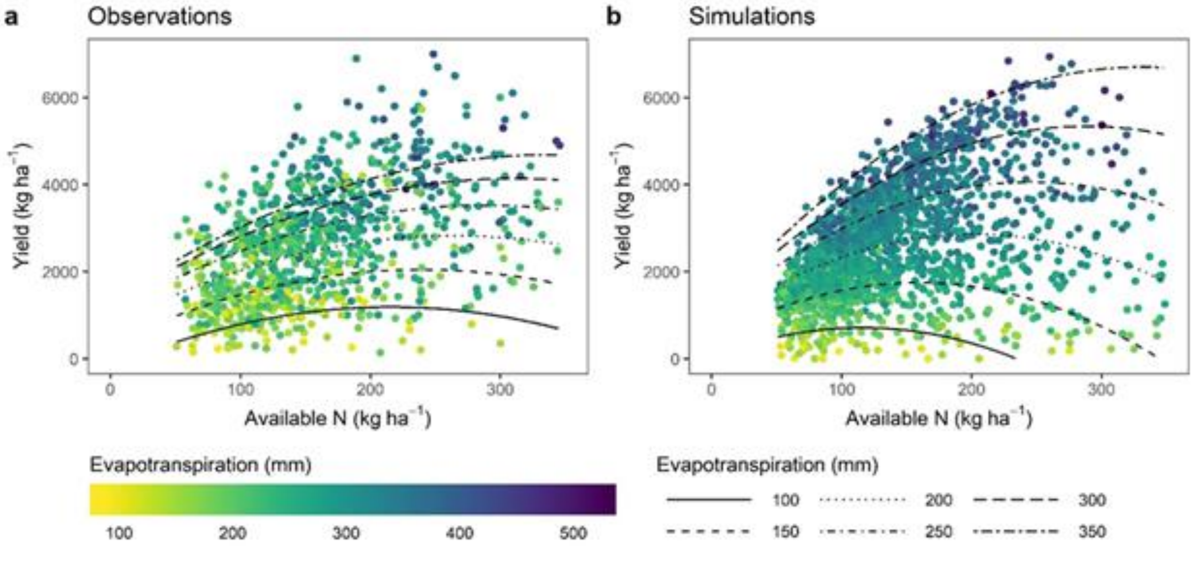

Figure 1. Wheat grain yield as a function of Available N (N) and Evapotranspiration (ET) for (a) observed and (b) simulated data. For the observed data yield was expressed as Y = -1523 + 9 x N - 0.029 x N^2 + 16 x ET - 0.023 x ET^2 + 0.03 x ET x N; (R^2 = 0.47; RMSE = 986 kg/ha; P < 0.001; N = 960). For the simulated data yield was expressed as Y = -1161 + 3 x N - 0.05 x N^2 + 14 x ET - 0.02 x ET^2 + 0.09 x ET x N; (R^2 = 0.73; RMSE = 681 kg/ha; P < 0.001; N = 1,814).

We further developed a simple tool to aid commercial wheat growers' decisions about in-season N fertiliser application rates (Figure 2a and 2b) in response to likely seasonal ET and users' ambition with respect to achieving 100%, 90% or 80% of their water-limited yield potentials.

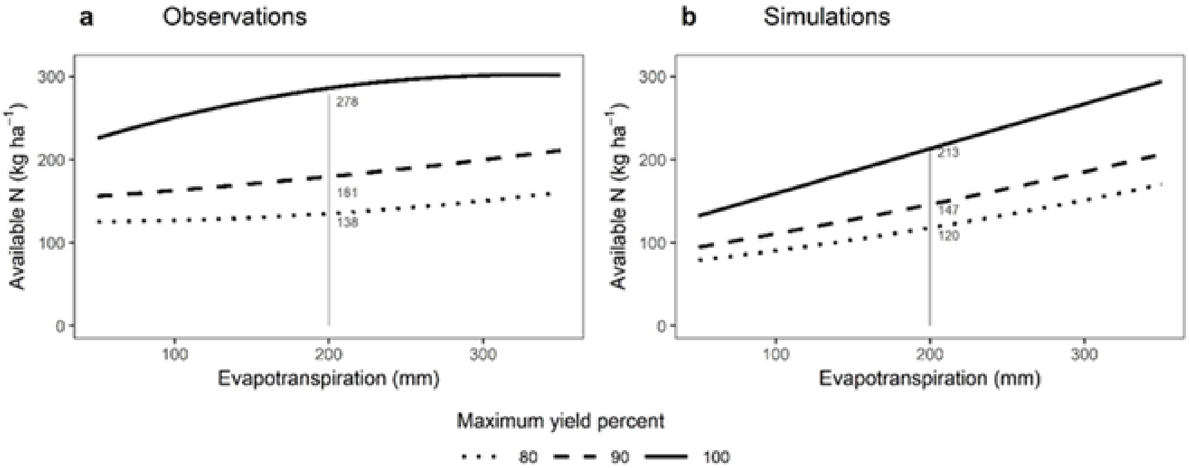

Figure 2: Illustration of the rate of N required to achieve water-limited yield (100%) as well as 90% and 80% of water-limited yield for a, the observed data set and for b, the simulated data set. As an example, required available N values (kgN/ha) are provided for Evapotranspiration = 200 mm.

Conclusion

While complex simulation models can relate wheat grain yield to available water and available nitrogen, their detailed data input requirements make them inaccessible to most growers who instead rely on simplistic rules of thumb. The practical implication for wheat growers and their agronomic advisers is that the combined formula could be developed as a decision tool that can be used to fine-tune their in-crop N application decisions. We propose that they first estimate the likely ET for their crop, based on ET to date plus an estimate of ET derived from either historic records or from seasonal climate forecasts, and then choose the level (%) of Yw that they intend to pursue. With these two numbers, they can apply the relationships obtained in Figure 2b to determine their N rate.

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