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Potential yield of wheat in the United Kingdom: How to reach 20 t ha^{-1}

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ABSTRACT

Given the need for increased yields in wheat, new cultivars will be wanted with higher potential yield (in optimal physical environment, without weeds, pests or diseases). The aim in the United Kingdom is 20 t ha^{-1}.

Potential yield can be predicted from the annual total solar radiation incident on the crop, the fraction of incident photosynthetically active radiation (PAR) which is intercepted, radiation use efficiency (RUE), and harvest index. The potential yield of current crops (interception of 0.46 of annual incident PAR; RUE 2.7 g MJ^{-1} dry matter above ground, intercepted PAR; harvest index 0.5) was 12–14 t ha^{-1} for annual solar radiation 3300–3800 MJ m^{-2} which is typical across wheat-growing regions of the United Kingdom. Many combinations of increases in interception (especially retention of green leaves into August and September), RUE and harvest index would achieve potential yields of 20 t ha^{-1} in sunny locations or sunny years with annual solar radiation of 3800 MJ m^{-2} or above.

Advancing growth duration by one month reduced yields because there was little radiation to be intercepted in March and much to be missed in July and August. If duration was advanced one month and extended by one month of maximum interception then yields were increased by around 16%.

From the relationships among yield, nitrogen concentrations of grain and straw, and nitrogen supply from soil and fertilizer, yields of 20 t ha^{-1} would require fertilizer application of 450–680 kg N ha^{-1} for breadmaking wheat (13% protein) and 350–580 kg N ha^{-1} for feed wheat (11% protein), with soil supply 100–200 kg N ha^{-1} and harvest index 0.5–0.6. If nitrogen application was restricted to the N-max limit for Nitrate Vulnerable Zones (440–500 kg N ha^{-1}) then 20 t ha^{-1} was achievable only with soil supply well above 100 kg N ha^{-1}.

Potential yield of wheat of 20 t ha^{-1} is possible in the United Kingdom from new cultivars with improved interception of radiation, RUE and harvest index (e.g. by 17%, 32% and 18%, respectively). Improved RUE can be exploited if optimum water and nutrients are maintained throughout crop duration. Increased harvest index raises yield and reduces straw and also produces a larger yield for a given amount of nitrogen supplied. High-yielding crops will require proportionate increases in nitrogen supply from the soil and fertilizer.

1. Introduction

It is generally agreed that world food production must increase substantially during this century (Godfray et al., 2010) and that much of this will come from staple crops such as wheat, rice and maize. Larger yields on a static or declining area of cultivated land will be required. Raising the potential yield of new cultivars will have a part to play in this, whether considered as a routine objective for plant breeders, or as a contribution to land sparing in agriculture (Lamb et al., 2016), or as part of system-wide agri-food research (Horton et al., 2017). We follow Fischer (2015) in using potential yield rather than yield potential (Evans and Fischer, 1999), where potential yield is the yield in an optimal physical environment (solar radiation, water, mineral nutrients, temperature), with complete protection from weeds, pests and diseases, and operations carried out with optimal timing, as can be achieved on research plots.

Wheat (*Triticum aestivum* L.) is the most important crop in the United Kingdom, grown on 1.8 million hectares each year (41% of arable area), producing about 15 million tonnes, with average yield hovering around 8 t ha^{-1} for nearly 20 years (Defra, 2016). Rothamsted Research has established an ambitious research programme called 20:20 Wheat (Rothamsted, 2016) to achieve potential yields of 20 t ha^{-1} within the next 20 years.

Having computed maximum theoretical yields for rice (Sheehy and Mitchell, 2015) of 18 t ha^{-1} (tropics) and 25 t ha^{-1} (subtropics), we wanted to know if wheat yields of 20 t ha^{-1} could be achieved in the U.K. For tropical and subtropical rice in relatively constant conditions it was possible to reduce the driving variables of the model to single

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values for solar radiation and temperature for the whole growth duration. This approach was not suitable for temperate wheat with a wide seasonal range of solar radiation and temperature. We used a model based on Monteithian growth analysis driven by solar radiation incident on the crop with monthly time steps (Monteith, 1977; Mitchell and Sheehy, 2006). The model can be seen as a rigorous expansion of the summary model for wheat breeding in Reynolds et al. (2011):

$$YP = LI \times RUE \times HI \quad (1)$$

where YP is potential yield;
LI is light intercepted;
RUE is radiation use efficiency; and
HI is harvest index.

The output from the model allows us to see where improvements in wheat characteristics will increase yields, and to explore the effects of changes in growing seasons. We extended the analysis to the mass balance of nitrogen in a wheat crop to calculate fertilizer requirements for high yields.

2. Methods

2.1. Equation for potential yield

In Monteithian growth analysis, accumulation of crop biomass (dry matter, DM) above ground is proportional to the accumulated interception of photosynthetically active radiation (PAR, 400–700 nm wavelengths). The constant of proportionality is the so-called radiation use efficiency: not a true efficiency with maximum value of one because it has units, here g MJ^{-1}. Radiation use efficiency (RUE) is also not a true constant but considered to have a conservative value for a given crop during vegetative growth in good growing conditions. For wheat growth during n months

$$Y = \frac{0.01}{0.85} H\varepsilon \sum_{i=1}^{n} (Q_i f_i) \quad (2)$$

where Y is yield (t ha^{-1}) at 15% moisture content (m.c.) which is 85% dry matter (oven dry);
0.01 (t 15% m.c. g^{-1} 15% m.c. m^2 ha^{-1}) converts from g m^{-2} to t ha^{-1};
1/0.85 (g 15% m.c. g^{-1} DM) converts from dry matter to 15% m.c.;
H is the harvest index, the fraction of dry matter above ground that is grain;
ε is radiation use efficiency (g MJ^{-1}, above-ground dry matter, intercepted PAR);
Q_i is the total incident PAR (MJ m^{-2}) for the ith month; and
f_i is the fraction of PAR intercepted, mean for the ith month.

The driving variable is Q_i, the monthly incident PAR, and this can be computed from solar radiation (300–3000 nm wavelengths) incident on a horizontal surface which is recorded by weather stations. As a long-term mean, the fraction of solar radiation (in energy units) that is PAR is consistently 0.50 (Szeicz, 1974; Stanhill and Fuchs, 1977; Stigter and Musabilha, 1982).

Assuming exponential interception of PAR down a canopy, the fraction intercepted (f) is

$$f = 1 - \exp(-kL) \quad (3)$$

where k is the extinction coefficient for PAR (m^2 ground m^{-2} leaf); and
L is the leaf area index (m^2 leaf m^{-2} ground).

From comprehensive measurements on winter wheat, a value for k of 0.46 for PAR is widely applicable (Thorne et al., 1988). Green area index (GAI) in cereals is taken as the equivalent of leaf area index. The GAI includes the one-sided area of all green tissues so including laminas of leaves, leaf sheaths, culms when exposed, and ears when present (AHDB, 2015). Monthly means for three patterns of wheat growth are given by Sylvester-Bradley and Kindred (2014). Current crops of winter wheat (WW, sown September to November to establish, then main growth period April to August the following year) are represented by benchmark values of GAI (AHDB, 2015), where benchmark crops are those on the best farms and in research trials. Two patterns for future crops were envisaged as targets for breeders, one WW and one spring wheat (SW, sown March to April for a continuous period of growth until harvest in August to September). The GAI and fraction intercepted month by month are given in Table 1.

Table 1
Seasonal patterns of green area index (GAI) and fraction of PAR intercepted as monthly means for canopies of wheat. Values for GAI are for benchmark WW, target WW and target SW from Sylvester-Bradley and Kindred (2014) with the names they used in brackets. The fraction intercepted is computed from Eq. (3) with a value for k of 0.46 (Thorne et al., 1988).

Month	Benchmark WW		Target WW		Target SW	
	(Normal)		(Potential autumn-sown)		(Potential spring-sown)	
	GAI	Fraction intercepted	GAI	Fraction intercepted	GAI	Fraction intercepted
April	2.0	0.60	2.5	0.68	1.0	0.37
May	6.0	0.94	6.0	0.94	3.5	0.80
June	6.3	0.94	7.0	0.96	5.0	0.90
July	3.0	0.75	4.0	0.84	5.0	0.90
August	0.1	0.04	1.3	0.45	4.0	0.84
September	0	0	0	0	1.3	0.45

The accumulated intercepted radiation could be site-specific, with interaction between incident radiation and the fraction intercepted. However, if a representative value can be obtained for interception by the canopy averaged over the year then it will be possible to predict potential yield from the annual total of incident solar radiation at any site. The weighted mean is

$$f_{year} = \frac{\sum_{i=1}^{n} (Q_i f_i)}{\sum_{i=1}^{n} (Q_i)} \quad (4)$$

where f_{year} is the mean fraction of incident PAR that is intercepted by the crop, weighted over the year by the incident PAR month by month;
f_i is zero in September or October to March in the following year with no interception of PAR;
n is 12 for the months in the year; and
the bottom line is the annual incident PAR.

This was computed with data from 19 weather stations (see §2.2) and for the three seasonal patterns of GAI given in Table 1.

An overall equation for yield (t ha^{-1} at 15% m.c.) can now be constructed as

$$Y = \frac{0.01}{0.85} H\varepsilon f_{year} 0.5 R_{year} \quad (5)$$

where 0.5 (MJ PAR MJ^{-1} solar radiation) converts solar radiation to PAR for use with ε and f_{year}; and
R_{year} is the annual incident solar radiation (MJ m^{-2}).

Inputs to the equation are listed in Table 2 with values used.

For spring wheat, growth duration occupies the one growing season so application of Eq. (5) is straightforward. For winter wheat there will be periods from September to March the following year when little or no growth is made because of low temperatures and small amounts of incident PAR. A constant value for RUE cannot be assumed during this period, and the fraction of PAR intercepted is small and difficult to measure precisely. The bulk of shoot biomass arises from growth in the main growing season, taken as starting in April. The crop which has stood over winter has a running start, as it were, by intercepting an appreciable fraction of incident PAR when growth can resume (Table 1). None of the leaves from winter persist into the summer biomass and their nitrogen is redistributed within the plant (AHDB,