A Yield Enhancement Network for oilseeds: estimating potential growth and yield

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Summary

On farm yields of oilseed rape in the UK have remained at around 3 t ha^{-1} since the 1980s. However, research trials and leading farms have often achieved yields above 5 t ha^{-1} and much larger bio-physical potential yields have been estimated for UK conditions of up to 9 t ha^{-1}. A Yield Enhancement Network (YEN) for oilseed crops was created in the autumn of 2016. The aim of this network is to support farmers, commercial and academic groups to analyse on farm yields, with the purpose of identifying ways of closing the innovation gap between potential and the best current farm and research yields. This paper describes a model to estimate the yield 'potential' of different environments, based on the solar radiation and water resources available to the crop and standard efficiencies of their conversion into crop dry matter. Based on assumptions of canopy size, rooting depth and resource use efficiency, UK yield potential has been estimated at between 8 t ha^{-1} in environments with restricted water supply to 14 t ha^{-1} with high levels of solar radiation and water.

Key words: Crop model, oilseed rape, radiation use efficiency, yield, yield enhancement, yield potential, water use efficiency

Introduction

UK oilseed rape yields on farm have been increasing slowly since 1983 at 0.011 t ha^{-1} yr^{-1} and currently average 3.2 t ha^{-1} (Knight *et al.*, 2012; Berry *et al.*, 2011). However, AHDB Recommended List (RL) small plot variety trials are averaging yields of more than 5 t ha^{-1}. The best farm yields are over 5 t ha^{-1} and some have been recorded as high as 6 or 7 t ha^{-1}. The slow improvement of average farm yields relative to varietal improvement have been attributed to a wide range of agronomic factors including slow uptake of new varieties, soil compaction, sub-optimal sulphur and nitrogen fertiliser timings and sub-optimal disease and pest control (Booth *et al.*, 2005; Berry & Spink, 2006; Knight *et al.*, 2012). The yield of current oilseed rape crops have been shown to be sink limited i.e. limited by the number of seeds per unit area (Berry & Spink, 2006). However, we anticipate that oilseed rape yields do not always need to be limited by seed number and could become source limited if this constraint can be alleviated. Berry & Spink (2006) predicted that if seed number could be increased to 150,000 m^{-2} then there would be sufficient capacity in individual seeds for the crop to become source limited. The light limited biophysical potential yield of UK oilseed rape has been estimated at 9.2 t ha^{-1} (Berry & Spink, 2006). The yield potential was estimated to be limited to between 6.7 and 8.7 t ha^{-1} for soils with lower water holding capacity in the drier east of the UK. This illustrates a substantial gap between the best farm/research yields and the biophysical yield potential, which we term as the innovation gap.

In order to make potential yields achievable on farm it is necessary to continually improve agronomy and management strategies alongside variety selection. This can be accomplished through better interaction of industry and the supporting science, promoting innovation and on farm yield testing. The Yield Enhancement Network (YEN) aims to address the challenge of closing the innovation gap by helping growers to see their crop as capturing and converting resources, hence helping them identify how best to maximise these. An Oilseed YEN was created in the autumn of 2016 as an extension of the Cereal YEN which originated in 2012. The calculation of site specific oilseed rape yield potential is important in this network in order to monitor yield achievements on farm, and make regional and national comparisons.

The yield potential estimated by Berry & Spink (2006) calculated the amount of dry matter that could be accumulated primarily during seed filling based on available light and water resources, together with an estimate of vegetative biomass that could be relocated to the seed. Haboketté (1997) also developed an oilseed rape growth model which took into account, amongst other factors, daily temperature, flower density and growth partitioning to vegetative matter and the seed. This paper outlines a simpler model requiring fewer parameters for estimating the biophysical yield potential of oilseed rape which accounts for growth over the whole growing period. This approach also allows potential dry matter accumulation to be estimated throughout the season and compared with crop growth on farm to monitor yield progress.

Materials and Methods

Calculating yield potential

Crop yields are universally considered to arise from the capture and conversion of light energy and water (Monteith, 1977). Nutrients are essential to dry matter production but here they are considered as facilitating capture and conversion of light and water, rather than as an essential component of biomass. Also, nutrients are readily available in fertilisers and manures, so their availability does not define potential growth. Although CO_2 is a vital resource for the production of dry matter through photosynthesis, it is not considered directly in this model due to the infeasibility of its manipulation and its variation being small over time and space (Sylvester-Bradley & Kindred, 2014).

As with the Cereal YEN, the YEN model for oilseed rape crops is based on as few assumptions as was deemed necessary to represent the independent roles of resource availability, capture and conversion; the potential value set for each trait is considered feasible through being derived from empirical observations of winter oilseed rape crops in the UK. These are then intended to provide benchmarks against which all Oilseed YEN entrants can monitor crop progress and devise strategies on farm which may enhance yield.

Potential light interception

Capture of incoming solar radiation is dependent on canopy green area and its disposition. The green canopy of oilseed rape is initially composed of leaves but after flowering becomes largely composed of pods; whilst leaf longevity could last longer after flowering, as in spaced plants, the majority of light interception in dense crops is by pods.

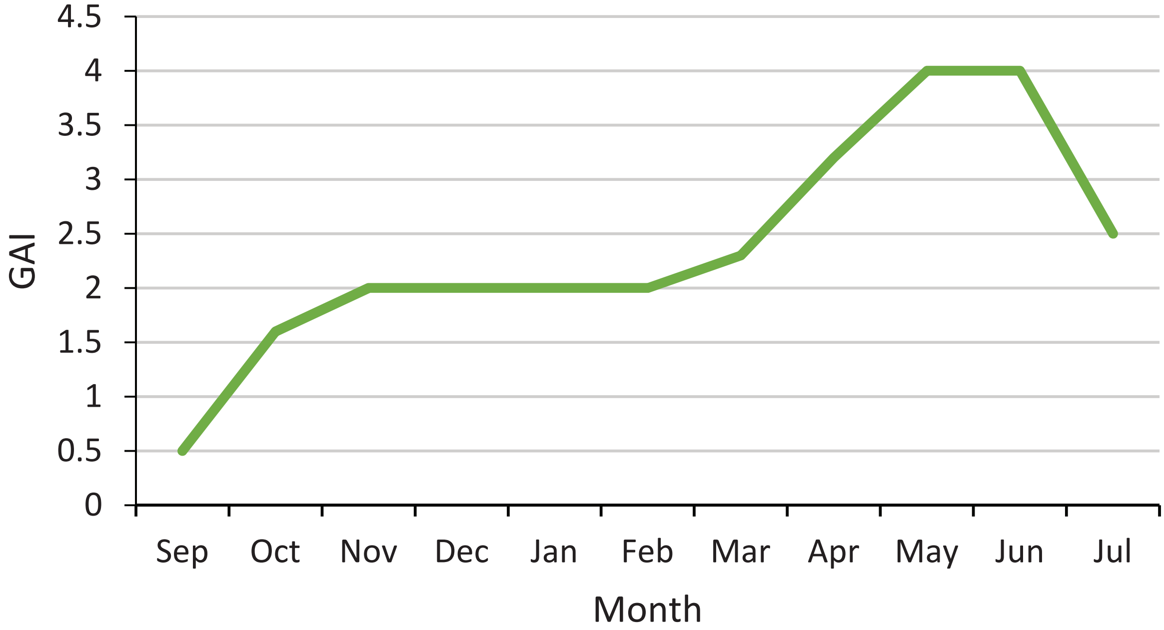

Fig. 1. Green Area Index (GAI) throughout the growing season for the potential yielding oilseed rape crop.

Green Area Index (GAI) is the ratio of green tissue area to the area of ground. Optimum monthly GAI values are used to determine potential percentages of light intercepted. Light reflection during flowering in oilseed rape is considered avoidable (e.g. by using apetalous varieties), so does not affect yield potentials. Optimum canopy size at flowering has been estimated previously between GAI 3 and 4 (Berry & Spink, 2006). In the yield potential model, optimum canopy size is consequently set at a GAI of 4 by mid flowering, occurring between mid-May and mid-June (Fig. 1).

In order to achieve the optimum canopy size at flowering, a GAI increasing from 0 to 2 is used from drilling until the end of October, sufficient to intercept 78% of radiation, assuming an extinction coefficient of 0.75 (Gabrielle *et al*., 1998). The extinction coefficient describes the efficiency of light interception based on solar radiation and the leaf area index (LAI). A low k is indicative of a high amount of light reaching the bottom of the canopy whereas a high k value indicates a low amount of light penetrating through the canopy. This would require drilling in late August with plant emergence at the start of September (Fig. 1).

The length of the growth period from mid flowering to physiological seed maturity, was 715 degree days (°Cd) above 4.2°C in cultivar Victor, grown in the UK. (Mendham *et al*., 1981). This duration would indicate that after mid flowering on May 1 then physiological seed maturity would be reached 68 days later (on July 7) in average UK conditions. Berry & Spink (2006) estimate the period from mid flower to the start of seed fill to be 25 days, giving a seed filling period of 43 days. The pod and seed development period is critical in determining yield. In the UK, late developing varieties now frequently do not reach harvest maturity until August which indicates that there is scope to extend the period of pod development and seed filling. The date of seed maturity for a potential yielding crop is therefore extended to July 31.

The percentage of light interception is calculated by:

$$1\text{-}exp\ (-k \times GAI)$$

where k is the light (or radiation) extinction coefficient. Values of k for total solar radiation have been reported between 0.6 and 0.75 (Mendham *et al*., 1981; Gabrielle *et al*., 1998; Morrison & Stewart, 1995). Radiation extinction coefficient values are larger in oilseed rape compared to cereals due to flatter oriented leaves and pods, values of 0.75 for both leaf and pod canopies has been set, resulting in the interception of 71% of total annual solar radiation in average UK conditions, given the GAI values in Fig. 1.

Potential radiation use efficiency

The maximum Radiation Use Efficiency (RUE) for C3 crops in the UK has been estimated as 1.4 t TJ^{-1} (Monteith, 1977). In oilseed rape this value changes through the season, determined by canopy architecture and temperature. RUE of oilseed rape before flowering has been measured at 1.2 t TJ^{-1} (Mendham *et al*., 1981), 1.35 t TJ^{-1} (Habekotté, 1997; Justes *et al*., 2000) and 1.7 t TJ^{-1} (Rao *et al*., 1991). The potential yield model assumes a maximum RUE of 1.4 t ha^{-1}.

Establishment to stem extension

During the winter months, photosynthesis is limited by lower temperatures and the crop can lose a substantial amount of biomass through shedding leaves, particularly during the vegetative phase. We cannot source measurements of RUE for oilseed rape during autumn and winter which account for losses of biomass in fallen leaves. Therefore, we have attempted to calculate the RUE over this period as follows. Prior to stem extension, oilseed rape crops have been shown to have on average a ratio of biomass (t ha^{-1}) to GAI of 1, up to a maximum of 1.4 (Berry & Spink, 2009). A crop with a GAI of 2 at the end of winter (Fig. 1) is therefore unlikely to carry a biomass of more than 3 t ha^{-1}. Over the autumn and winter period we estimate that our potential yielding crop will intercept 5 TJ based on the GAI described in Fig. 1. This indicates a net RUE of 0.6 t TJ^{-1} over the autumn/winter period after accounting for biomass lost in fallen leaves and lower photosynthetic rates in cool winter conditions.

Stem extension to seed fill

RUE measurements taken from the literature were measured after stem extension and therefore are more reliable indicators for the yield potential model during this period. At flowering, oilseed rape crops can reflect up to 60% of the incoming light and consequently reflection can reduce RUE. However, we assume through breeding and technological developments this can be eliminated, for example by exploiting apetalous cultivars or cultivars with smaller flowers. Therefore, a value of 1.4 t TJ^{-1} is given for RUE from the start of stem extension to the start of seed fill.

Seed fill to senescence

Producing oil rich seed in oilseed rape plants requires 1.45 times more assimilate for each gram of seed in comparison to vegetative dry matter (Sinclair & de Wit, 1975). This effect will reduce maximum potential RUE to 1.0 t TJ^{-1}. Additionally, pods have a reduced photosynthetic capacity compared to leaves, estimated between 50% and 70% (Gammelvind *et al*., 1996) and previous measures of RUE during seed filling have reported values of 0.4 t TJ^{-1} (Habekotté, 1997) and 0.75 t TJ^{-1} (Dreccer *et al*., 2000). Due to the reduced photosynthetic capacity of pods and greater energy required to produce seed the yield potential model uses an RUE of 0.7 t TJ^{-1} during seed fill. Average UK annual solar radiation is around 35 TJ ha^{-1} which, based on the stated RUE and GAI through the season (Table 1), the potential yielding crop will accumulate 24 t ha^{-1} of crop dry matter using the equation: solar radiation × *(1-(exp(-k × GAI) × RUE*.

Water availability and its potential capture

In the UK soils are replenished to field capacity over the winter period and therefore water available to the crop is the soil water holding capacity at the start of spring plus the spring and summer rainfall, assuming all rainfall during this period (March to June) is available to the crop. Rooting depth has previously been measured in oilseed rape to reach up to 1.5 – 1.8 m (Barraclough, 1989). The proportion of crop-available water that is accessible by the roots has been measured at 65 – 68% in oilseed rape, to a depth of 1.5 m (Barraclough, 1989). In this model it is assumed that a potential yielding crop would have the ability to root to 2 m depths and increase percentage of water available to the plant to 75%.

Table 1. *Radiation Use Efficiency (RUE, t TJ^{-1}) values used in yield potential model per month*

	Establishment – Stem extension						Stem extension – Seed fill			Seed fill – Senescence	
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
RUE	0.60	0.60	0.60	0.60	0.60	0.60	1.40	1.40	1.40	0.70	0.70
GAI	0.53	1.60	2.00	2.00	2.00	2.00	2.30	3.22	3.99	4.00	2.50
k	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Potential water use efficiency

Water use efficiency (WUE) in oilseed rape has been measured in controlled environments between 3.4 and 6.0 g L^{-1} in differing CO_2 concentrations and nitrogen treatments (Franzaring *et al*., 2011). However, due to lack of evidence for oilseed rape in field conditions, it is assumed that the WUE of a high yielding crop is 5 g L^{-1}, as has been reported for wheat, which is also a C3 crop (Foulkes *et al*., 2001). This amounts to the production of 1 t of biomass for every 20 mm of water used. In the potential yielding oilseed crop we anticipate that there is scope to increase this by 10%, giving a maximum of 5.5 t of biomass per 100 mm of water used, before seed filling. Due to the high energy requirement for producing oil rich seed, this value declines to 3.8 t ha^{-1} per 100 mm of water in keeping with RUE. If stem extension is expected to start on 1 March and seed filling to end on 31 July, with approximately 2 months seed filling, then 47% of the radiation intercepted during this period will be used for seed filling. This will give a weighted average WUE of 4.7 t per 100 mm during this period. We estimate that, to support this potential biomass growth without water limitation, the total water supply to a crop from 1 March would need to exceed 425 mm calculated using: *light limited dry matter accumulated up to March + (soil AWC + Spring and Summer rainfall) × WUE.*

Potential harvest index

High harvest indices previously reported in the literature for OSR include 0.40 at low plant populations (Lunn *et al*., 2001), 0.42 for a semi-dwarf variety (Berry *et al*., 2012) and 0.45 for a late sown crop (Mendham *et al*., 1981). The scope to reduce stem biomass is limited at higher yield potentials as this may increase lodging. Therefore a maximum harvest index of 0.45 is assumed to define the potential yielding oilseed rape crop.

Results

Yield potentials for oilseed crops in the UK were calculated using long term average (LTA) Met Office data for a medium retentive soil with a total available water content to 2 m depth of 210 mm (Fig. 2). Yield potentials ranged from 8.7 t ha^{-1} in the south east to 14.7 t ha^{-1} in the south west (Fig. 2c). Yields below 10.6 t ha^{-1} were generally water limited with most of these occurring in the east of the UK, where spring and summer rainfall is lowest (Fig. 2a). Whereas the highest yields are achieved in the south west and west coast of the UK and limited by light, due to summer rainfall being sufficient for the crop to produce its potential biomass even though the available annual solar radiation is high (Fig. 2b). Whilst the yield potentials in the map are indicative of our beliefs, yield potentials will differ for individual entrants because their soil types will differ from that assumed here. Available water at field capacity is calculated using site soil depth, stone content and texture of the top- and sub-soil. Interestingly, estimated potential yields are least in the main area where oilseed rape is normally grown.

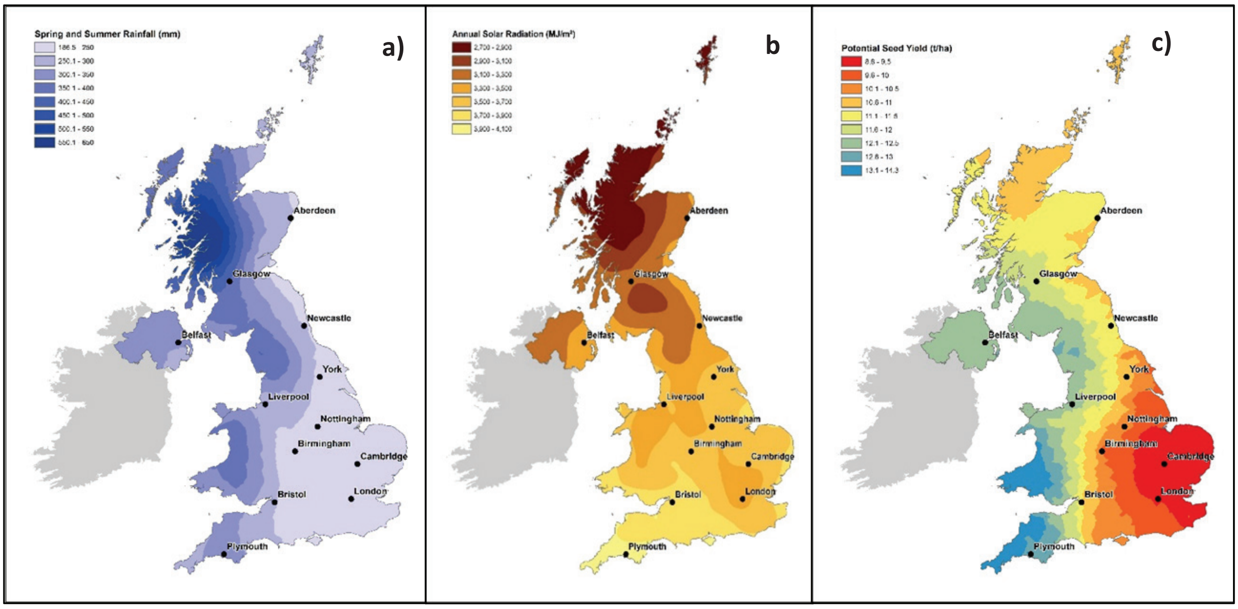

Fig. 2. Maps of the UK showing a) LTA spring and summer rainfall (March–June), b) LTA annual solar radiation and c) estimated potential yield based on LTA solar radiation and spring and summer rainfall, for soils with a medium water holding capacity of 210 mm.

Discussion

The Yield Enhancement Network (YEN) aims to promote innovation and the testing of yield enhancing techniques. Calculating yield potentials of oilseed rape helps growers to see their crop's performance as resulting from the capture and conversion of resources. By identifying how a crop has fallen short of its potential we propose that they should see better which traits to manipulate in order to reach a greater proportion of their yield potential. The model proposed here is designed with as few input parameters as possible to facilitate the ability to monitor and reason about growth in relation to light and water resources during the season. The main differences in relation to previous models estimating potential yields of oilseed rape are that it accounts for growth over the whole growing period, considers maximum plausible harvest index and requires fewer inputs. The potential yields here are similar to those estimated by Berry & Spink (2006) at 9 t ha^{-1} on water retentive soils in the main oilseed rape growing areas in the east of the UK. Further west in the UK the potential yield is greater reaching 14 t ha^{-1} where light and water resources are greater.

Compared with oilseed rape crop characteristics as they are currently grown in the UK (described in (Berry & Spink, 2006), it would appear that the main differences proposed in the potential yield model here are the extension of the pod and seed development period and increase of the radiation use efficiency during flowering and pod development. Harvest index is also increased quite substantially which is a consequence of greater biomass accumulation post flowering. The yield potential model proposes little change to canopy size but proposes an optimum canopy size that ensures more efficient use of light and the prevention of an over-sized canopy reflecting a lot of light at flowering and increasing the risk of lodging.

The yield potential model is directly applicable for winter oilseed rape. Only minor modifications maybe required to make applicable for spring oilseed rape primarily involving delaying the calendar dates of the main phases of crop development. A number of the yield formation processes are applicable for other oilseed species such as sunflowers and linseed, but more substantial development is likely to be required to make the yield model applicable for these crop species.

If the Oilseed YEN can attract increasing numbers of entrants each season, the increasing amount of data collected should enable a better understanding of on farm oilseed yields and the major factors accounting for the performance of these crops at a local level. This data can be used to draw conclusions on where effort should be focused to help growers capture more water, more light or increase conversion efficiencies to biomass. With each entrant providing dates of sowing, harvest and critical growth stages during the season, variations in the lengths of important growth periods can be used to identify any potential means of manipulation.

The YENs also aim to promote industry and academic involvement, to focus discussion and research on yield enhancement at the field level. It is expected that this will emphasise the importance of new approaches to field management and growing systems rather than solely on genetic improvements, in order to close the gap between potential and current yields.

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