Modelling the effect of temperature and photoperiod on the faba bean (*Vicia faba* L.)

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Abstract

N-fixing legume crops may be a good component of a general plan to improve cropping system efficiency. For this purpose, crop suitability to specific environments must be established. Irrigated field experiments were conducted for three years (2004–2007) with cv. 'Alameda' sown on five different dates in each year.

This article examines the phenologic response of the faba bean (*Vicia faba* L.) crops to various thermal and photoperiod regimes. For this purpose first the authors have used the concept of the development rate (inverse to duration) developed by Wit et al. (*The simulation of photosynthetic systems*, 1970) and the development rate as the inverse of the time between sowing and flowering (1/f) defined by Hadley et al. (*Effects of temperature and photoperiod on flowering in soya bean [Glycine max (L.) Merril]: a quantitative model,* 1984). In this way, if a crop has a long period between sowing and flowering (*f*: days), it will have a low development rate (*1/f*: days^{-1}), so it can then analyse the length of the period by means of the *1/f* the development rate. In second place families of mathematical models have been obtained by applying the methodology developed by Villacampa et al. (*A new computational algorithm to construct mathematical models*, 1999) and Cortés et al. (*A new methodology for modelling highly structured systems*, 2000) that will be compared with the linear model widely used for legumes (Summerfield et al. *Measurement, prediction and genetic characterisation of flowering in Vicia faba and Pisum sativum*, 1991). In the family of models produced it will select those that best express the crop phenologic response in different phenologic stages.

Keywords: mathematical modelling, stability, faba bean, phenology, legumes, photoperiod, temperature.

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1 Introduction

Nitrogen supplied by symbiotic fixation in legume nodules is considered fundamental for economically and environmentally sustainable production (European Union, 1991). The faba bean (*Vicia faba* L.) is the seventh most important grain legume in the world (FAO, 2006) and is used for both human and animal nutrition. In Europe, with 17% of the world's production (FAO, 2006), the main use is as animal feed (Sau [6], Mínguez et al. [7], Rees et al. [8]). The nitrogen-fixing capabilities of the faba bean, enabling them to produce substantial yields without the necessity of nitrogen fertiliser, make them also attractive as break-crops in arable rotation (Confalone [9]).

Studies on the phenology and optimal conditions for each phase of the crop cycle are essential in searching for the most suitable species and sowing times for particular regions (Iannucci et al. [10]).

Although temperature is the most important factor controlling the rate of legumes development, other factors such photoperiod may modify its effects (Confalone [9]). However, little is known about the correlation between photoperiodic and temperature effects on forage legume development. In different legumes, photoperiod and temperature strongly affect time to flowering, but not in the same way for all species, suggesting genotypic variation for sensitivity to both photoperiod and temperature (Iannucci et al. [10]).

A family of relatively simple linear models has been proposed to represent the flowering behaviour of a range of both long and short-day plants (Summerfield et al. [5]).

To analyse flowering in soybean, Hadley et al. [2] used the concept of developmental rate (D, day^{-1}) – developed by Wit et al. [1], defined as the inverse of the time between emergence and flowering (1/f), which is then related linearly to photoperiod and temperature variables. In general, the effects of photoperiod and temperature have proved to be additive. This very useful approach to analyzing flowering resulted in a good description of D as a linear function of mean temperature (T) and mean photoperiod (P):

$$1/f = D = a + bT + cP$$

where a, b and c are empirical coefficients. The values of T and P were defined as the mean over the entire interval from emergence to flowering.

The objectives of this study were to (i) use the linear models in assessing the relative contributions of temperature and day length to rate of flowering as well as in other phonological sub-periods of the crop. (ii) to obtain new models for estimating rate of development from temperature and photoperiod.

2 Material and method

The study was carried out over a period of three agricultural seasons (2004-2007) in an experimental field of the *Escola Politécnica Superior* at the *University of Santiago de Compostela*, in Lugo, Spain (43º04' N; 7º30' W;

altitude 480 m). The soil, classified as Humic Dystrudept (USDA-SMSS, 1994), was fertilized with P and K before sowing to avoid any limitation of these nutrients. Soil-water availability was maintained close to field capacity for all treatments using drip irrigation when required. The water to be applied in each irrigation was calculated as the product of reference evapotranspiration (estimated with the Penman-Monteith equation) and the corresponding crop coefficient for the faba bean (Allen et al. [11]), less the amount of precipitation in the period considered. Crops were also maintained free of pests, diseases and weeds. Agrometereological information was recorded daily by an automatic weather station located close to the experimental field.

The faba bean cultivar '*Alameda*' was obtained from the *Mejora y Biotecnología de Cultivos* Department of the *Instituto de Investigación y Formación Agraria* (*IFAPA, Junta de Andalucía, Córdoba, Spain*). The cultivar is classified as an intermediate type between botanical varieties *majo*r and *equina* (Cubero [12]) and has an indeterminate growth habit.

Treatments consisted of five sowing dates during the period from early fall to late spring. In Table 1, the sowing dates and dates of occurrence of stages

Table 1: Sowing dates and dates of occurrence of stages of crop development.

Crop stage [1]	**1st**	**2nd**	**3rd**	**4th**	**5th**
	2004-2005				
Sowing date	11/05/04	12/15/04	02/17/05	03/29/05	05/05/05
Emergence	28	36	34	33	14
1st flower	140	115	83	69	45
1st pod	166	138	93	75	52
Phys. maturity	234	201	153	127	98
	2005-2006				
Sowing date	10/26/05	12/13/05	02/10/06	04/04/06	05/02/06
Emergence	18	48	34	17	13
1st flower	152	125	82	52	45
1st pod	176	136	91	65	55
Phys. maturity	226	199	145	108	96
	2006-2007				
Sowing date	10/30/06	12/20/06	02/16/07	03/27/07	04/30/07
Emergence	13	33	19	19	13
1st flower	129	102	81	59	49
1st pod	167	125	96	72	64
Phys. maturity	225	198	158	128	105

[1] Fehr et al. [13].

of crop development (days after sowing) can be seen for three growing seasons and five planting dates in faba bean:

1st: end October – early November
2nd: mid December
3rd: mid February
4th: end March – early April
5th: end April – early May

Sowing dates were assigned to the experimental plots in a randomised complete-block design, with three replications, and 45 m^2 per experimental unit. Plant population density was 35 plants m^{-2} in rows 0.35 m apart.

Plants were monitored at 2-3 day intervals to determine crop emergence, anthesis, beginning pod, full seed, and physiological maturity dates (Fehr et al. [13]). Plots were considered to be in a particular growth stage, when 50% of the plants had reached a developmental stage.

3 Mathematical modelling

In order to quantify the effect of photoperiod and temperature on the duration of different phenological periods of the *faba bean (Vicia faba* L.) using mathematical models, we initially considered the development rate concept and the methodologies developed in (Spss [14]; Cortés et al. [4]; Villacampa et al. [3]). The linear models for each phenological period are the same for each methodology. To obtain non-linear models, we used the methodology developed in Villacampa et al. [3] and Cortés et al. [4] as it allows us to obtain families of non-linear models, which were generated from a language, and of which we chose those that best represented the phenological periods.

The results obtained allow us to state that the linear models corroborate the contribution of temperature in all the phenological periods modelled, as well as the increased importance of the photoperiod from sowing to maturity. Of the families of non-linear models, we chose the same kind of model for each phenological period on the basis of their simplicity. Additionally, they did not differ greatly from the linear models.

We have included a study of the stability of all the models selected, applying the methodology developed in Villacampa et al. [15] and Verdú and Villacampa [16]. In the said methodology, perturbations were applied to the experimental data to study their effect in the model, this being an ideal information parameter for identifying the validity of the model. An unstable model is not valid for inferring situations similar to those being studied from the initial data. In order to appreciate the stability, we show the graph of the function that determines the variations produced in the model (OY axis) graphically, when applying perturbations of a certain percentage to the data (OX axis). All the models are stable, except for the non-linear model in the period of maturity, this being unstable.

3.1 Mathematical models for the period from sowing to seedling

Linear model:

$$\frac{1}{f} = D = -0.011 + 0.006262\ T + 0.00001\,F\ ;\quad R^2 = 0.91$$

Non-linear model:

$$\frac{1}{f} = D = 0.0104 + 0.00026\ T^2 + 0.0014\ T + 0.00001\,F^2 - 0.00005\,F\ ;\quad R^2 = 0.92$$

If we apply perturbation of 20% to the experimental data, the models are seen to be stable.

3.2 Mathematical models for the period from seedling to flowering

Linear model:

$$\frac{1}{f} = D = -0.007 + 0.0021\ T + 0.0003\,F\ ;\quad R^2 = 0.96$$

Non-linear model:

$$\frac{1}{f} = D = 0.0043 + 0.0001\ T^2 + 0.00044\ T + 0.00005\,F^2 - 0.0005\,F\ ;\quad R^2 = 0.96$$

If we apply perturbation of 20% to the experimental data, the models are seen to be stable.

3.3 Mathematical models for the period from flowering to first pod stage

Linear model:

$$\frac{1}{f} = D = -0.0165 + 0.0071\ T - 0.0015\,F\ ;\quad R^2 = 0.96$$

Non-linear model:

$$\frac{1}{f} = D = -0.013 + 0.000223\ T^2 - 0.000042\ T + 0.0000595\,F^2 - 0.000212\,F\ ;\quad R^2 = 0.97$$

If we apply perturbation of 20% to the experimental data, the models are seen to be stable.

3.4 Mathematical models for the period from first pod to maturity stage

Linear model:

$$\frac{1}{f} = D = 0.0228 + 0.001284 \ T - 0.0017 \ F \ ; \quad R^2 = 0.85$$

Non-linear model:

$$\frac{1}{f} = D = \left(\text{-}0.0116 \ T + 0.14515\right)^2 + \left(0.00504 \ F - 0.199854\right)^2 ; \quad R^2 = 0.88$$

If we apply perturbation of 20% to the experimental data, the models are seen to be stable.

4 Results

The five sowing dates provided a wide range of environmental conditions to examine the performance of the faba bean *cv*. `Alameda´ (Table 2).

As the sowing time was delayed, the crop was exposed to higher values of daily solar radiation, and temperature, and longer photoperiod resulting in a shortening of the crop cycle. Although the crop was irrigated to maintain soil moisture close to field capacity, Table 2 shows that in the first sowing date average (three year experiment) cumulative precipitation exceeded average atmospheric demand by 60%. On the other hand, the last two sowing dates (4th and 5th) showed a clear need for irrigation with average unsatisfied atmospheric demand in the order of 57% and 68% for this relatively cool. In the 1st sowing date of the first experiment, the light hours were getting shorter after emergence, producing the lowest photoperiod values between 15th and 30th December. The photoperiod increased from 13.3 to 14.7 h during the Flowering-1st Pod phase (113 – 139 days after emergence, DAE). The 2nd sowing date on the other hand, although it was sown at a time when the light period was getting shorter (middle of December), in the time from emergence to flowering (80 DAE) the photoperiod increased from 10.6 to 14.1 h. In the 3rd sowing date, the crop grew under increasing photoperiod up to 90 DAE, from 13.2 h to 16.6 h. The latter two thirds of the pod filling stage occurred under decreasing photoperiods. In the 4th sowing date, only during the pod filling phase plants were exposed to decreasing photoperiods, whereas in the 5th sowing date plants grew after flowering under decreasing photoperiods (16.6 to 15.1 h). A detailed account of crop phenology on each growing season and sowing date is reported in Table 1, including daily values of solar radiation (SRAD), maximum (Tmax) and minimum (Tmin) temperature and photoperiod (P), and cumulative values of precipitation (Cum Prec) and reference evapotranspiration (Cum ETo) for five sowing dates averaged from emergence to physiological maturity for three growing seasons (coefficient of variation in parentheses).

Table 2: Duration of crop cycle and agrometeorological conditions.

Trt	*Crop cycle* (d)	*SRAD* (MJ m^{-2} d^{-1})	**Tmax** *(ºC)*	**Tmin** (ºC)	**P** (h)	**Cum Prec** (mm)	**Cum ETo** (mm)
1st	209 (0.01)	11.8 (0.07)	14.8 (0.02)	4.2 (0.15)	13.9	562.8 (0.25)	354.1 (0.08)
2nd	161 (0.05)	15.5 (0.07)	17.1 (0.03)	5.6 (0.02)	14.2	259.3 (0.26)	257.9 (0.25)
3rd	124 (0.12)	18.9 (0.03)	20.3 (0.04)	8.1 (0.13)	15.2	268.4 (0.11)	380.1 (0.08)
4th	99 (0.09)	21.3 (0.06)	23.1 (0.06)	10.1 (0.10)	15.8	153.9 (0.51)	356.6 (0.01)
5th	87 (0.05)	22.0 (0.05)	24.4 (0.07)	11.2 (0.09)	15.9	109.5 (0.63)	339.1 (0.03)

For all phenological sub-periods considered, the growth rate, expressed as the opposite of the duration of the sub-period, showed strong correlation with the additive linear model for temperature and photoperiod, with a significant response to temperature ($p< 0.05$) at all stages and a non-significant effect for the photoperiod. This may be due to a lack of sensitivity of the bean crop used or also to that demonstrated with other species, where the effect of temperature on growth is greater than the photoperiodical effect, this being masked by the fact that the data comes from field trials where there is significant correlation between photoperiod and temperature. (Massingnam and Angelocci [17]). This is why some writers state that controlled environmental conditions should be used to identify the response of certain crops to the photoperiod (Goyne and Hammer [18]). However, the simplicity of the model, which uses average values recorded for these two environmental variables over the phase studied, may make it difficult to statistically detect the variable with least impact.

The models in question, both linear and non-linear, are valid for examining phenological periods, and they were stable when carrying out perturbations of up to 20% in the phenological stages. Although new experimental data should be studied so that they may be validated, and the authors also need to obtain new non-linear models to compare with the models obtained in this paper.

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