Adapting the CROPGRO Legume Model to Simulate Growth of Faba Bean

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ABSTRACT

Crop growth models are valuable tools for integrating our understanding of physiological processes and for hypothesizing and evaluating crop management strategies. Our objective was to adapt the CROPGRO model to simulate the growth and yield of faba bean (*Vicia faba* L.). The CROPGRO model simulates different grain legume species using external parameter files that describe species process sensitivity to environment plus files describing cultivar differences. Specific objectives were to develop a species file and one cultivar file for faba bean based on: (i) values and relationships from the literature and (ii) comparison with observed growth data on faba bean grown in Cordoba (Spain). A systematic procedure was followed to develop relationships and values for the species and cultivar files. Base temperatures for processes of this cool-season legume are typically between 0 to 2°C for photosynthetic, vegetative, and reproductive processes while corresponding optimum temperatures vary from 22 to 30°C. After adaptation, the model accurately predicted total crop dry matter accumulation, pod mass, and partitioning to plant components. High seed yields of faba bean exceeding 6000 kg ha^{-1} were predicted in agreement with observed data. Sensitivity analyses on sowing date showed optimum yields from early winter sowing at Cordoba and late winter sowing in northern Europe. Adapting an existing mechanistic model such as CROPGRO had advantages because many processes were similar across species and well simulated. The primary adaptation required was to change the cardinal temperature sensitivities of growth processes, based on faba bean literature or by analogy to other species.

C ROP MODELS ARE VALUABLE TOOLS for synthesizing our understanding of physiological processes, hypothesizing genetic improvement, and evaluating crop and soil management strategies (Boote et al., 1996). In this paper, our objective was to adapt the CROPGRO grain legume model to simulate the growth and yield of faba bean (*Vicia faba* L.). Although there is a model for faba bean developed by Stutzel (1995a, 1995b), adaptation of the CROPGRO model was desired to take advantage of the modular subroutines in CROPGRO that simulate soil water balance, soil N balance, soil organic matter–residue dynamics, pest and disease damage, and other processes. In addition, adaptation of CROPGRO allowed us to use the weather handling, risk management, and GIS–spatial programs and to take advantage of the standard input–output file conventions of the DSSAT models (Hoogenboom et al., 1994a; Jones

et al., 1994; Tsuji et al., 1998). Using CROPGRO also allowed us to capture greater physiological detail of leaf-level photosynthesis coupled to hedge-row photosynthesis, explicit nodule growth and N$_2$ fixation, plant uptake of N from the soil, growth and maintenance respiration, internal plant carbohydrate, and N balance.

CROPGRO is a mechanistic, process-oriented model for grain legumes that includes crop development, C balance, crop and soil N balance, and soil water balance subroutines (for details, see Boote et al., 1998a, 1998b). Crop development includes processes such as vegetative and reproductive development, which determine life cycle duration, duration of root and leaf growth, onset and duration of reproductive organs such as pods and seeds, and thereby influence dry matter partitioning to plant organs over time. Crop C balance includes daily inputs from photosynthesis, conversion and condensation of C into crop tissues, C losses to abscised parts, and growth and maintenance respiration. The C balance also simulates leaf area expansion, growth of vegetative tissues, pod addition, seed addition, shell growth, seed growth, nodule growth, senescence, and carbohydrate mobilization. The crop N balance includes daily soil N uptake, N$_2$ fixation, mobilization from vegetative tissues, rate of N use for new tissue growth, and rate of N loss in abscised parts. Soil N balance processes are similar to those described by Godwin and Jones (1991). Soil water balance processes include infiltration of rainfall and irrigation, runoff, soil evaporation, distribution of root water uptake, drainage of water below the root zone, and crop transpiration (Ritchie, 1998). The time step in CROPGRO is mostly daily (corresponding to daily recording of weather information) but is hourly for some processes, such as the leaf-level hedgerow photosynthesis. Model state variables are predicted and output on a daily basis for crop, soil water, and soil N balance processes.

The CROPGRO model is a generic model that uses one common FORTRAN code to predict the growth of a number of different grain legumes {soybean [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), and dry bean (*Phaseolus vulgaris* L.)} as well as other crops such as tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a, 1998b). This versatility is achieved through input files that define species traits and cultivar attributes. More information on CROPGRO's generic nature and file input structure is available in Hoogenboom et al. (1994b) and Boote et al. (1998a, 1998b). Having one common generic code allows code improvements in the basic model, e.g., for

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Abbreviations: HI, harvest index; LAI, leaf area index; +N, N fertilized; −N, unfertilized; PD, photothermal day; RLD, root length density; SLA, specific leaf area; Tb, base temperature; Tmax, maximum temperature; Tmin, minimum temperature; Topt, optimum temperature.

soil water balance, soil organic matter–N balance, or soil temperature to be directly available for all of the crops. The approach has helped minimize *hard-wired* coefficients in the code for aspects that characterize individual species. This generic-model approach with its read-in species and cultivar traits has helped us in modifying CROPGRO for other species, such as cowpea (*Vigna unguiculata* L.) (Boote, unpublished, 1998), chickpea (*Cicer arietinum* L.) (Singh and Virmani, 1994), and nonlegumes such as tomato (Scholberg et al., 1997). For each given species, the CROPGRO species file contains knowledge about base temperatures (Tb) and optimum temperatures (Topt) for developmental processes (rate of emergence, rate of leaf appearance, and rate of progress toward flowering and maturity) and growth processes (photosynthesis, nodule growth, N_2 fixation, leaf expansion, pod addition, seed growth, and N mobilization, etc.). Either short or long daylength effects on development during specific life cycle phases are allowed by the species file, with two parameters in the cultivar file indicating each cultivar's critical short (or long) daylength and the slope of daylength sensitivity that slows development at increasingly longer (or shorter) days. The species file also includes coefficients and other relationships for photosynthesis, N_2 fixation, tissue composition, and growth and maintenance respiration.

While our primary objective was to adapt CROPGRO for faba bean, an ancillary objective was to describe the process of adapting the model for a new species. The latter question is important for more mechanistic models, which on the surface, would appear to have many complex processes and relationships, yet literature information on processes and relationships for a given species may be lacking. We propose that, despite their apparent complexity, processes such as photosynthesis, respiration, and N assimilation are quite conserved (repeatable) across species and that the main differences relate to cardinal temperatures, daylength sensitivities, and timing of reproductive and partitioning events. Thus, we are able to start with processes well simulated for other legume crops and modify their temperature sensitivities, based substantially on literature information or by analogy to other cool-season species or contrast to warm-season species. In this paper, contrasts of this cool-season crop are made relative to temperature sensitivities of warm-season legumes simulated by CROPGRO. In addition, the adaptation process should also involve developing relationships and parameters by comparison to observed experiments. The faba bean model developed in this way would be expected to be well grounded in physiological principles and ready for further testing for diverse conditions, locations, and faba bean types. In this study, we make initial comparison only to growth under nonlimiting water conditions.

MATERIALS AND METHODS

Approach for Model Adaptation

To adapt CROPGRO for faba bean, we followed two approaches to develop the required species file and cultivar traits based on: (i) values and relationships reported from the literature and (ii) comparison to observed experimental growth analyses data on faba bean grown in Cordoba, Spain, during two seasons. In addition, we documented literature sources for deriving relationships needed for the species file and described the process of developing species and cultivar coefficients from experimental data. Our initial starting point was the CROPGRO–dry bean model version (Hoogenboom et al., 1994b) as we thought its species file was closer to faba bean than that of the other grain legumes. This was true for the lower cardinal temperatures and low oil-composition seed; however, in retrospect, faba bean is more like soybean and peanut in that it is a long-lived legume with excellent N_2 fixation and high photosynthesis.

A systematic procedure was followed, similar to that described by Boote (1999). First, values such as tissue composition, Tb and Topt for processes, and critical N concentrations for photosynthesis were obtained from the literature. Some relationships obtained from the literature were subsequently modified upon comparison to field data. Second, we adjusted photothermal day (PD) threshold values so as to correctly predict crop life cycle, anthesis and maturity dates, each in sequence. This process was extended by comparison to data on similar cultivars in France and by comparison to observed phenology for sowing dates of the specific cultivar in Spain. Third, predicted biomass accumulation and leaf area index (LAI) were compared to observed values, using actual weather and management input data, and used for calibration of photosynthesis and leaf growth parameters. Fourth, comparisons of predicted vs. observed timing of pod growth and increase in pod harvest index (HI) were made in addition to evaluating dry matter partitioning among leaf, stem, and pod components. Features such as timing from anthesis to first pod, anthesis to first seed, and duration of pod addition were adjusted as well as allocation among leaf, stem, and root before reproductive growth. Fifth, nodule growth, leaf N concentration, and N decline during grain fill were evaluated and adjustments made on parameters and temperature sensitivities affecting nodule growth, N_2 fixation, and N mobilization. Sixth, seed size, seeds per pod, and single-seed growth rate and duration were adjusted to reproduce correct seed size, seed growth duration, and threshing percentage. There was considerable iteration between the third, fourth, fifth, and sixth steps outlined here where comparisons were made visually to observed growth analyses data.

Faba Bean Experiments—Materials and Methods for Phenology, Yield, and Growth Analyses

The experimental data used for model calibration came from irrigated treatments of two field experiments sown 10 Dec. 1986 (Exp. 1) and 24 Dec. 1987 (Exp. 2) on a deep alluvial, low-impedance soil (Typic Xerofluvent) at Cordoba in the middle Guadalquivir Valley, southern Spain (38° N, 4° W; 90 m elevation). In both cases, soil pH in water was 7.1. Before sowing, the soil was fertilized with adequate amounts of P and K according to soil tests. Furrow irrigation was practiced, as necessary, to avoid water deficit. Weather data were summarized by Sau and Mínguez (2000).

The two faba bean cultivars, Alameda (in both experiments) and Brocal (only in the second experiment) are classified as indeterminate botanical varieties (*V. faba* var. *major* L. and *V. faba* var. *equina* L., respectively) (Cubero, 1974). In Exp. 1, plant density and row spacing were 19 plants m^{-2} and 0.7 m, respectively, while in Exp. 2, they were 33 plants m^{-2} and 0.6 m, respectively. In each year, two N treatments were imposed: N fertilized uninoculated (+N) or unfertilized inoculated (−N).

In +N treatments, the N was supplied as three applications of urea (at sowing, beginning bloom, and end of bloom), for a total amount of 200 and 300 kg N ha^{-1} in Exp. 1 and 2, respectively. Treatments were replicated four times. A more detailed experimental description can be found in Sau and Mínguez (2000).

Dry matter accumulation of stems, petioles, leaves, flowers, and pods was measured and leaf area recorded at 15-d intervals based on sampling of 0.35 to 0.37 m^2 of plant material from each plot. A three-plant subsample was separated into stems, petioles, leaves, flowers, and pods. All of the subsample components and remaining plants were dried separately to constant weight in a convective oven at 70°C for more than 48 h. Leaf area was determined with a LI-COR planimeter Model LI-3000. Crop height and row width (tip of the upper leaf of a plant and width of the shadow at solar noon, respectively) were measured 4 and 10 times, respectively, in each plot every 5 to 10 d. Root length density (RLD) along the soil profile was measured three times during both experiments by soil coring and the modified Newman method (Newman, 1966), as described by Alvarez de Toro (1987). At final maturity, large plots (8 m^2 land area) were harvested to determine total crop mass, pod mass, seed yield, and HI.

RESULTS AND DISCUSSION
Adaptation Based on Literature Review
Vegetative and Reproductive Development Rates—Temperature

Several sources were used to document Tb and Topt for vegetative and reproductive development. Qi et al. (1999) reported that Tb is 0 to 1°C for emergence and −1 to −2°C for rate of leaf appearance. From their data, developmental rates were most rapid at 27°C (assumed as lowest optimum temperature, Topt1), but there were no treatments above 27°C. Data from Evans (1957) suggested that rate of node appearance has a Topt1 of 23°C, with a slight downturn at 26°C. Manschadi et al. (1998b) reported Tb of 1.5°C for germination to emergence (based on unpublished data). As summarized in Table 1, Tb of 0°C and Topt1 of 27°C were used for both rate of emergence and rate of leaf appearance. There is little

data available on Tb and Topt for rate of progress to anthesis and to maturity although Evans (1957) reported Topt1 of 22°C for reproductive development of French winter type and a Topt1 of 17°C for Bullock winter type. In addition, Evans (1957) found slower progress toward flowering at mean temperature above 22°C. A Tb of 0°C is proposed for reproductive development (Table 1) because it is consistent with the vegetative processes and has been used by many researchers (Plancquaert and Girard, 1987; Stutzel, 1995a; Manschadi et al., 1998b). Manschadi et al. (1998b) used Stutzel's 1995 model and assumed an upper threshold of 20°C for reproductive development, using daily mean air temperature [(Tmax + Tmin)/2]. Following results of Evans (1957), a Topt1 of 22°C was used for progress to anthesis as well as progress during late reproductive development (beginning seed to maturity). The highest Topt (Topt2) for progress to anthesis was assumed to be 26°C, based on Evans' (1957) finding that development rate was slower above 26°C. For rate of progress from anthesis to maturity, Topt2 of 35°C was selected (Table 1).

Reproductive Development—Long Day Effect

Faba bean is a quantitative long-day plant although there are few data documenting critical long daylength requirement or sensitivities to daylength change other than data of Evans (1957) and Tamaki et al. (1974). Days to flower decreased linearly as daylength was increased from 8 to 24 h for several widely varying faba bean types (Evans, 1957). Except for one spring type, the slope of days to flower vs. daylength was the same for all types, but the types differed in the apparent intercept to the longest daylength at which rate of development was most rapid (range was 12 h for spring type to more than 24 h for the slowest winter type). We concluded that there is a wide array of faba bean types such that degree-day–oriented coefficients without daylength sensitivity may work for spring types in Germany (Stutzel, 1995a, 1995b) and the Netherlands (Grashoff and Stokkers, 1992) but not for winter types grown in France,

Table 1. Cardinal temperatures—base (Tb), first optimum (Topt1), second optimum (Topt2), and maximum (Tmax)—and shape of function† used for growth processes of faba bean vs. soybean for use by CROPGRO model.

Growth or development process	Shape	Faba bean				Soybean			
		Tb	Topt1	Topt2	Tmax	Tb	Topt1	Topt2	Tmax
		°C							
Development, rate of node expression	Linear	0	27	30	40	7	28	35	45
Development, reproductive, to first seed	Linear	0	22	26	45	6	26	30	45
Development, reproductive, first seed to maturity	Linear	0	22	35	45	−48	26	34	45
Light-saturated leaf photosynthesis, LFmax‡ vs. current temperature	Linear	1	30	31	40	8	40	40	48
Light-saturated leaf photosynthesis, LFmax vs. Tmin§	Quadr.	−2	14	−¶	−¶	0	19	−¶	−¶
Nodule relative growth rate, Tsoil#	Linear	1	16	25	40	7	22	35	44
Nodule specific nitrogenase act, Tsoil	Linear	1	16	25	40	5	20	35	44
Leaf relative expansion (SLA††)	Linear	2‡‡	20	−¶	−¶	12‡‡	22	−¶	−¶
Internode expansion (height and width)	Linear	0‡‡	18	−¶	−¶	12‡‡	26	−¶	−¶
Pod addition and seed addition	Quadr.	6	15	24	34	14	21	27	40
Seed growth rate	Quadr.	2	18	21	36	6	21	24	41

† Rate is as fast as possible between Topt1 and Topt2, approaching zero at either Tb or Tmax following either a linear shape or a quadratic shape.
‡ LFmax, maximum leaf photosynthetic rate.
§ Tmin, minimum temperature.
¶ Relative rate remains high above Topt1.
# Tsoil, soil temperature.
†† SLA, specific leaf area.
‡‡ For this case, relative rate is 0.25 at Tb.

Table 2. Genetic coefficients of cultivars Alameda and Brocal for the CROPGRO model, after the calibration process.

Genetic coefficients	Alameda	Brocal
Critical short daylength above which reproductive development progresses with no daylength effect (CSDL) (h)	24.0	24.0
Slope of the relative response of development vs. photoperiod (PP-SEN) (1/h)	−0.031	−0.031
Time between emergence and flower appearance (EM-FL) (PD†)	18.0	18.0
Time between first flower and beginning pod (FL-SH) (PD)	11.0	10.5
Time between first flower and beginning seed (FL-SD) (PD)	26.0	25.5
Time between beginning seed and physiological maturity (SD-PM) (PD)	31.8	29.5
Time between beginning seed and end of leaf expansion (FL-LF) (PD)	45.0	45.0
Maximum leaf photosynthetic rate at 30°C, 350 μL L^{-1} CO$_2$, and high light (LFMAX) (mg CO$_2$ m^2 s^{-1})	1.0	1.0
Specific leaf area of cultivar under standard growth conditions (SLAVR) (cm^2 g^{-1})	285.0	300.0
Maximum size of full leaf (SIZLF) (cm^2)	110.0	110.0
Maximum fraction of daily growth that is partitioned to seed + shell (XFRT)	1.0	1.0
Maximum weight per seed (WTPSD) (g)	1.1	1.1
Seed-filling duration for pod cohort under standard conditions (SFDUR) (PD)	21.0	21.0
Seeds per pod at standard growth conditions (SDPDV) (no. pod^{-1})	2.4	2.4
Duration of pod addition under standard conditions (PODUR) (PD)	18.0	18.0
Maximum shelling percentage [seed × 100%/(seed + shell)] at maturity (THRESH) (%)	77.0	77.0

† PD, photothermal days.

Spain, and the Mediterranean. Evans (1957) found evidence of vernalization in the winter types; however, this was the only reference in the literature. Therefore, vernalization was ignored and long-day effects (acceleration) up to anthesis for winter types was used.

The effect of long daylength was previously introduced into the CROPGRO model for the chickpea version (Hoogenboom, unpublished, 1998) and requires specifying a critical maximum long daylength, at which progress to anthesis is most rapid, plus a slope of daylength sensitivity that decreases rate of progress at shorter day lengths. A *maximum long daylength* of 24 h was assumed, based on results of Evans (1957) for a French winter type. This is also consistent with the approach of Stutzel (1995a) in which rate of progress toward flowering depends on a multiplicative function of daylength times mean temperature below 20°C threshold. Stutzel's equations imply a Tb of 0°C, a critical maximum long day of 24 h, and a critical minimum long day of 0 h. In addition to a critical maximum long day of 24 h, we used an apparent sensitivity (PP-SEN) that defines the slope of cultivar sensitivity to long days (these are cultivar traits in Table 2). By comparison to literature values, a slope of (−0.052) was required to mimic the daylength sensitivity of French winter types. This follows the suggestion of Plancquaert and Girard (1987) that later sowing dates give later dates of accumulation of 500°C-d from 1 January to 80 d later and should give a decrease from 1250 to 900°C-d for the time from sowing to anthesis. This function gives a slower rate at the 9- to 10-h daylengths prevalent in winter in faba bean growing regions of Spain, moving toward more rapid rate in late spring as daylength becomes longer. Later comparison to five sowings of a Spanish winter bean type suggested a slope of −0.031 for this type.

Both Stutzel (1995a) and Plancquaert and Girard (1987) suggest that faba bean is accelerated toward anthesis by long days but that reproductive phases after anthesis are not sensitive to daylength. This assumption was accepted; however, given the presence of daylength sensitivity after anthesis in soybean and dry bean, we are not convinced of the issue for faba bean. Indeed, Stutzel (1995b) mentions a shortening of the reproductive phase from anthesis to maturity (in degree-days)

with later sowing dates although this was attributed to pest attack.

Tissue Composition, Growth Respiration, and Protein and Carbohydrate Mobilization

Composition of faba bean seed (32.5% protein, 1.5% lignin, 3.5% ash, 2.0% lipid, 3.0% organic acids, and 57.5% carbohydrate-cellulose) was based on values from Hill-Cottingham (1984). The compositions for seed and vegetative tissues are specified in the species file, except for seed protein (SDPRO) and seed lipid (SDLIP), which are cultivar traits (Table 2). Internally, the CROPGRO model computes the growth respiration costs and conversion efficiencies for tissues based on these six approximate compositions, following the method of Penning deVries and van Laar (1982). For leaves, stems, pod walls, and roots, composition values were taken from dry bean, except for leaf protein concentration, for which faba bean data were available. CROPGRO requires three values for protein composition of leaves and other tissues: the luxury consumption value (maximum value under high N fertilization), the typical value for nodulated legumes, and the minimum concentration at which all available protein is exhausted at leaf senescence and photosynthesis is nearly zero. Based on five references for faba bean cited in Reuter and Robinson (1997), we set the luxury value at 5.5% (0.344 protein), the typical leaf N concentration at 4.7% (0.294 protein), and the minimum N at 1.8% (0.112 protein). One reference listed deficient N concentration as varying from 1.6 to 2.5%; thus, the minimum N concentration was set at 1.8% based on soybean as soybean leaves have similar adequate and luxury N values as faba bean (Reuter and Robinson, 1997; Boote et al., 1998a).

CROPGRO allows protein mobilization from vegetative tissues, including leaves, as a function of age, particularly accelerated during seed fill. This function (NMOBMX) was set such that leaf N concentration approaches 2.3% N at physiological maturity, thereby mobilizing most of the available protein to the exhausted level (about two-thirds of the total vegetative protein is eventually transferred to seeds). As faba bean leaf photosynthesis depends on leaf N concentration,

photosynthesis was set to be a quadratic function, increasing from zero at 1.8% N to maximum rate at 5.5% N. By comparison, the function for soybean photosynthesis goes from 1.9 to 5.5% N. Coefficients for carbohydrate storage and mobilization in vegetative tissues were accepted from the dry bean species file and found to work satisfactorily. These coefficients create a given level of available carbohydrate in newly produced vegetative tissue, allow carbohydrate to accumulate during periods of N deficit, provide for carbohydrate storage in stems and leaves upon the transition from anthesis until setting a full seed load, and allow subsequent mobilization of carbohydrates for growth.

Photosynthesis

For growth processes such as photosynthesis, Tb and Topt were not available from the literature. There is little data on temperature effects on leaf or canopy photosynthesis of faba bean, except for anecdotal data of Sale (1977), who stated that there was no influence of daytime temperature down to 5°C on canopy assimilation of faba bean. Because there were no data on leaf photosynthesis, Tb and Topt of leaf photosynthesis were approximated from those for emergence and rate of leaf appearance. Thus, a Tb of 1°C, Topt1 of 30°C, Topt2 of 31°C, and maximum temperature (Tmax; zero rate) at 40°C were used for light-saturated leaf photosynthesis (Table 1). Light-saturated leaf photosynthesis has a more linear response to temperature because it depends mainly on electron transport rate. By contrast, quantum efficiency decreases as temperature increases. The resulting use of these two contrasting functions in the module of leaf-level canopy photosynthesis gives a very broad Topt for canopy rate (Boote and Pickering, 1994). The CROPGRO model allows an additional minimum night temperature effect (Tmin) on the next day's photosynthesis. For soybean, this function has an asymptotic response increasing from 0.0 at 0°C to 1.0 at 19°C. We presumed that faba bean sensitivity to night temperature is less than that of soybean; thus, the asymptotic function for night temperature effects on the next day's leaf photosynthesis was set to −2 (Tb for zero rate) and 14°C (asymptotic value with no limit on rate) (Table 1). The model is quite sensitive to this parameter, especially during early to midseason when night temperatures were frequently ≤10°C and the canopy was increasing in size. The respective Tb and Topt1 values are 4 and 22°C for peanut, 0 and 19°C for soybean, and 0 and 16°C for dry bean. Thus, by comparison, faba bean is presumed to be less affected by Tmin (night temperature) than these species.

Faba bean has the C_3 pathway of photosynthesis, based on composite data cited by Peat (1984), but there is minimal useful field data, except for that of Sale (1977). Sale (1977) reported that peak net canopy assimilation rate of faba bean is 50 mg CO_2 dm^{-2} h^{-1} in full sun for LAI of 7. The CROPGRO model predicts gross canopy assimilation (before CO_2 losses from growth and maintenance respiration). During rapid growth (full canopy LAI of 6), and using faba bean composition,

CROPGRO predicts that 34.6% of assimilates are concurrently respired for growth and maintenance respiration. Converting Sale's (1977) value of 50 mg CO_2 dm^{-2} (land area) h^{-1} to 1.39 mg CO_2 m^{-2} s^{-1} and dividing by (1.000 − 0.346) gives us 2.12 mg m^{-2} s^{-1} as the target rate of gross instantaneous canopy assimilation. This value is consistent with rates measured on soybean canopies (Boote et al., 1984) where instantaneous crop dark respiration including roots and nodules was measured to be 30 to 40% of gross instantaneous assimilation. A midday canopy gross assimilation rate of 2.12 mg CO_2 m^{-2} s^{-1} requires that upper sunlit leaves have a light-saturated rate between 1.0 to 1.2 mg CO_2 m^{-2} s^{-1} (Boote and Pickering, 1994). Using the CROPGRO model, predicted rates of gross canopy assimilation were 2.0 to 2.1 mg CO_2 m^{-2} s^{-1} for faba bean at noon and LAI > 6 in nonlimiting temperatures, with input of leaf assimilation rate of 1.00 mg CO_2 m^{-2} s^{-1}. [Maximum leaf photosynthetic rate (LFMAX) in Table 2 is defined at light saturation, 30°C, 350 µL L^{-1} CO_2, 21% O_2, and a reference specific leaf weight of 0.0035 g cm^{-2}.] Actual predicted leaf photosynthesis at midday during midseason was somewhat higher, 1.1 to 1.2 mg CO_2 m^{-2} s^{-1}, because upper leaves are modeled to have greater specific leaf weight than lower leaves.

Nodule Growth and Dinitrogen Fixation

Reports on nodule growth and N_2 fixation of faba bean indicate good rates of N_2 fixation that continue late during peak fruit growth (Cooper et al., 1976). A field study conducted in Alaska (Sparrow et al., 1995) showed that faba bean had the highest N_2 fixation rates of all the legume species tested, highest N accumulation, and high total plant N concentration (2.9 and 3.0% at *final* harvest). With the tissue compositions set as described previously, the model predicts average total plant N concentration of about 2.9 to 3.0% during most of the latter half of the growth period. From these references, faba bean appears to have excellent cool-temperature tolerance for nodule growth and function. It should be noted that the CROPGRO model uses model-computed soil temperature to influence nodule growth and specific activity. The functions (of soil temperature) affecting nodule growth rate and specific activity were set appropriately, so lags in nodule growth and rate of N_2 fixation were no more limiting than air temperature effects on rate of photosynthesis and dry matter gain. Maximum specific nodule activity (SNACTM) was set to 0.050 g of N_2 fixed per gram of nodule mass per day (compared with 0.045 for soybean), initial nodule mass (DWNODI) to 0.03 g per plant because of large seed size (compared with 0.015 g for peanut), and a maximum relative nodule growth rate (NODRGM) to 0.22 g g^{-1} d^{-1} (compared with 0.20 g g^{-1} d^{-1} for peanut). For temperature response, we set Tb, Topt1, Topt2, and Tmax to 1, 16, 25, and 40°C, respectively, for nodule growth rate as well as specific nodule (nitrogenase) activity (Table 1). The Tb and Topt1 values are 4 to 6°C less than respective values for soybean and 3 to 5°C less than values used for dry bean and were set to give a

response that creates minimal dip in leaf N concentration (because of lack of N_2 fixation) and keeps the maximum nodule mass at $<150\,kg\,ha^{-1}$ dry matter, consistent with low nodule mass observed in this study.

Vegetative Expansion Processes

In CROPGRO, two factors affect the time to end of leaf area expansion: First, there is a photothermal time after anthesis (FL-LF PD, a cultivar trait in Table 2) during which expansion can continue, and second, within that phase, leaf area expansion continues as long as assimilate is partitioned to leaves (terminates naturally when all assimilate is going to reproductive organs). Thus, this is a mixed function ultimately limited by degree of determinacy. By comparison, Stutzel (1995a) stopped vegetative stage development when dry matter partitioning to leaf ends.

CROPGRO has several ancillary functions by which temperature, light, and water affect leaf area expansion, canopy height, and canopy width. A primary effect of temperature already discussed is on rate of node (leaf) appearance (Table 1). Temperature, light, and water deficit have additional effects on leaf area expansion and internode elongation per se, resulting in altered specific leaf area (SLA), canopy height, and canopy width. The temperature function affecting SLA is assumed to have a Tb of 2°C, where expansion is 0.25 of optimum, and a Topt1 of 20°C where expansion occurs at the optimum rate (Table 1). Temperature sensitivity of internode elongation assumes Tb of 0°C and Topt1 of 18°C, giving 0.25 of normal internode length at 0°C and linearly increasing to 1.0 of normal internode length at 18°C (Table 1). There is no evidence supporting these values, other than Tb of 0°C being used for related processes such as rate of node appearance. Auld et al. (1978) reported that leaf expansion is decreased by temperature in the range of 14 to 23°C and that leaf area expansion decreases at high irradiance. CROPGRO includes a light history effect, whereby increasing light causes decreased internode length and lower SLA. In addition, CROPGRO computes a turgor factor (TURFAC), which can decrease internode elongation and the SLA of today's leaf growth. The latter two features were unchanged from the dry bean and soybean coefficients.

Crop height and width are predicted by CROPGRO as a function of increase in main-stem node number and of successive internode length. Vegetative node number over time was reasonably well predicted (data not shown), using 0.35 nodes PD^{-1}, a Tb of 0°C, and Topt1 of 27°C. CROPGRO's species file has a lookup array that defines maximum potential internode length for successive nodes above the cotyledonary node. We started with values for soybean, which is of similar node number and height. Like soybean, early internodes are shorter, and successive nodes become longer until about two-thirds of the final node number are expressed. In addition, internodes are predicted to be shorter as a function of water deficit and cool temperature. With these calibrations, we were able to reasonably predict canopy height and width over time (simulations not shown). Canopy height and width have their impact in the model only via light interception of the hedgerow canopy photosynthesis model used in CROPGRO (see Boote and Pickering, 1994).

Pod Addition, Seed Addition, and Seed Growth

The CROPGRO model begins to add pods at the beginning pod stage (which occurs at FL-SH PD after anthesis, Table 2]. Pods are added for a photothermal-dependent duration (PODUR, Table 2) at a rate that depends on current canopy assimilation rate and current temperature. After a given duration (FL-SD, a cultivar-dependent number of PD after anthesis, Table 2), seeds are added in the cohorts as they reach appropriate pod age defined by FL-SD minus FL-SH. There were no data on Tb and Topt for pod addition and seed addition; therefore, we set temperature effects on faba bean by analogy to common bean and soybean values. For example, soybean has Tb, Topt1, Topt2, and Tmax of 14, 21, 26.5, and 40°C, respectively, for pod addition, whereas dry bean has Tb, Topt1, Topt2, and Tmax of 7, 13, 25, and 36°C, respectively. Soybean is reported to have temperature sensitivity that limits pod addition at temperatures well above the Tb of 7°C used for vegetative growth. Dry bean is less sensitive to cold and was given a Tb of 7°C for pod addition, only 3°C above the Tb used for vegetative node formation (Hoogenboom et al., 1994b). By analogy for faba bean, we used Tb, Topt1, Topt2, and Tmax of 6, 15, 24, and 34°C, respectively, for pod addition (Table 1) where the Tb for pod set is 6°C above the Tb for vegetative growth. Seed growth rate has a different function, again set for faba bean by analogy to dry bean and soybean values. Soybean uses Tb, Topt1, Topt2, and Tmax of 6, 21, 23.5, and 41°C, respectively, set from data of Egli and Wardlaw (1980), and dry bean uses Tb, Topt1, Topt2, and Tmax of 6, 21, 23, and 36°C, respectively. For single-seed growth rate of faba bean, we set Tb, Topt1, Topt2, and Tmax to 2, 18, 21, and 36°C, respectively (Table 1), close to reported temperature coefficients for vegetative and reproductive development of faba bean.

Cultivar-Specific Values for Phase Durations and Other Traits

So far, we have described the defining and setting of species file traits, without discussing specific cultivars. Similar to other grain legume species, there are substantial cultivar differences within faba bean particularly related to life cycle differences. The CROPGRO model uses cultivar and ecotype files to quantify how cultivars and major groups of cultivars differ with respect to durations of the life cycle phases, daylength sensitivities, seeds per pod, seed size, determinacy of both pod addition and leaf area growth, SLA, leaf photosynthesis rate, relative internode length, and canopy width, etc. (Table 2).

Cultivar and ecotype coefficients can be derived from phenological observations and growth analyses recorded in field experiments or from values reported in

variety trials and publications when weather data are available. Typically, the values from the literature need to be *filtered* or *rescaled* to give the PD units (or other units) used in CROPGRO. In this approach, the CROPGRO model was run with weather data, and degree-days were computed as defined by French and German scientists and, at the same time, translated to PD. In this way, PD were derived from the following reported degree-day values: time to emergence (140°C-d, from Manschadi et al., 1998b), time to anthesis [1100°C-d for French cultivar minus 10 to 15 calendar days equivalent by which Spanish cultivars were reportedly earlier flowering; this compares well to 734 to 865°C-d from emergence to anthesis reported for the Alameda cultivar grown at Madrid (Oliveira, 1995)], and time from anthesis to maturity (1535°C-d, from Plancquaert and Girard, 1987). Oliveira (1995) reported 1078 to 1148°C-d from anthesis to maturity for Alameda sown at Madrid, Spain, but our computed values for the same cultivar in our study were close to 1500°C-d. Likewise, we derived PD durations for time from anthesis to beginning pod (200°C-d from Stutzel, 1995a), time from anthesis to rapid seed growth (550–600°C-d, Plancquaert and Girard, 1987; Stutzel, 1995a), and duration of flowering and pod addition (PODUR) (410°C-d, from Plancquaert and Girard, 1987). These cultivar thresholds were set initially from literature reports on other cultivars and subsequently evaluated to see if the phase durations worked for the Alameda cultivar in our study.

Model Adaptation Based on Growth Analyses

Additional model adaptation for faba bean was focused on changes to improve simulations by comparison to observed growth, development, dry matter accumulation, and partitioning of the Alameda and Brocal cultivars grown in our study. Results in figures and tables show simulations after final adaptations, illustrate the how and why of adaptation, and are not intended as a validation statement. In the prior section, species file aspects presumed to be generic for faba bean were taken from literature, but these came from many different cultivars. Thus, it is not surprising that the comparison to observed data for the Alameda cultivar required not only minor changes to the species files, but also setting of the cultivar–ecotype file parameters for these cultivars (traits in Table 2).

Life Cycle

In order to set the daylength sensitivity coefficient and thresholds determining flowering and maturity for the Alameda cultivar, the life cycle of that cultivar was calibrated from data on days to anthesis for the 1986–1987 and 1987–1988 experiments in Cordoba (85 and 83 d to anthesis, respectively) and also from three widely varying sowing dates for 1999–2000 in Lugo (119, 80, and 66 d to anthesis). Days to maturity came only from the Cordoba study. The Lugo environment exposed the crop to much cooler conditions during winter plus a wider range of daylengths. Based on these data, the slope of the relative response of development vs. photo-

period (PP-SEN) for the Alameda cultivar was made less sensitive to long days (from −0.052 for French winter types to −0.031), and the basic phase duration (EM-FL) was set to 18.0 d (Table 2). The root mean square error for predicting anthesis for these five cases was 2.41 d. These coefficients (EM-FL and PP-SEN) were used for the subsequent simulations for both Alameda and Brocal, but coefficients affecting timing of pod set, timing of seed set, and time from rapid seed to maturity were later subject to minor modifications after comparing with observed onset of pod and seed growth.

Biomass Accumulation

After calibrating anthesis and maturity parameters as above and setting species parameters and relationships to the extent possible based on independent literature, we compared simulated growth of faba bean with observed crop biomass and pod mass in 1986 and 1987 seasons, both during the season (Fig. 1) and at final harvest (Table 3). Only final simulations are shown in the figures and Table 3 because our objective was to calibrate and adapt a new model for a first comparison,
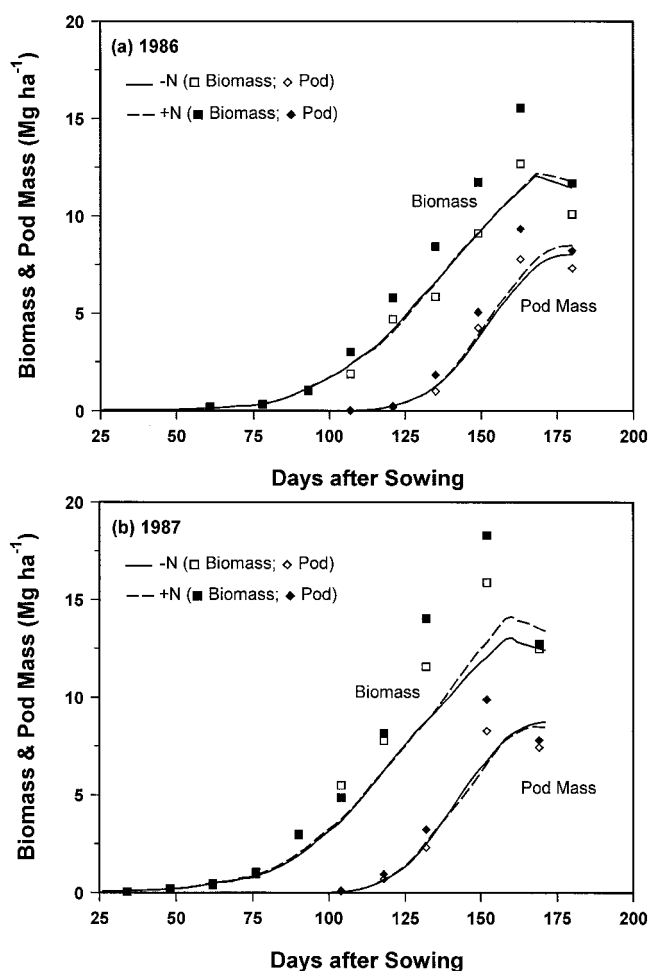

Fig. 1. A comparison of simulated (lines) and observed (symbols) crop biomass and pod mass as a function of days after sowing for faba bean cultivar Alameda grown in Cordoba, Spain, in (a) 1986 and (b) 1987. +N, fertilized uninoculated; −N, unfertilized inoculated.

Table 3. Comparison of observed and simulated life cycle and crop variables at maturity averaged over six treatments of faba bean (two on Alameda in 1986, two on Alameda in 1987, and two on Brocal in 1987), and the root mean square error (RMSE).

Crop variable	Observed mean	Simulated mean	RMSE
Anthesis, d	83.7	82.7	3.0
Maturity, d	162.7	160.7	2.2
Crop mass, kg ha^{-1}	12 047	12 375	774
Seed yield, kg ha^{-1}	6 328	6 375	370
Seed HI†	0.532	0.516	0.052
Final node no.	20.8	20.2	0.82
Total crop N, kg ha^{-1}	351	349	25.1
Seed N, kg ha^{-1}	282	280	15.4
Seed N conc., g kg^{-1}	44.5	43.9	0.19

† HI, harvest index.

not to *validate* it. Model evaluations were made against both the −N and +N treatments because the observed and modeled differences between these treatments were minor. In addition, simulations were compared with data on the Brocal cultivar in 1987 (not shown in Fig. 1, but included in Table 3). Thus, Table 3 illustrates model predictions and root mean square errors for crop variables measured at final harvest and averaged over six treatments of the two years. Model parameters dealing with dry matter accumulation were calibrated primarily to the final harvest sample because of the large land area involved (8 m^2), and less emphasis was placed on fitting magnitude of in-season biomass and pod mass (0.35–0.37 m^2). It is generally accepted that final yield samples of large areas are more reliable (lower variation) and less subject to inflation from poor bordering than small growth analysis samples (in this case, ratio of land area was 22:1). Final comparisons showed slight underprediction of slope of dry matter accumulation but correct prediction of final biomass and pod yield (last sample dates in Fig. 1 and Table 3). Only minor modifications were needed for the canopy photosynthesis functions. Indeed, the maximum leaf photosynthetic rate (LFMAX) was unchanged and comparable to soybean and dry bean while changes were made primarily to functions affecting early season assimilation when the canopy was small and temperatures were cool. These were related to Tmin effect on photosynthesis and also attributed to incorrect partitioning to leaf and stem, which was resolved by calibration of partitioning as described later.

Timing of Pod Growth

Time from anthesis to beginning pod (FL-SH) and to beginning seed (FL-SD) had only been previously set from literature on other cultivars. Thus, initially, the timing of pod growth and pod HI was early by a few days, despite correct prediction of anthesis date for the Alameda cultivar. Moreover, rate of pod addition also impacts apparent onset of pod HI, and there was no literature information on this parameter. As a result, we modified three coefficients for the Alameda cultivar [increased FL-SH from 9 to 11 d, increased FL-SD from 25 to 26 d, and decreased time between beginning seed and physiological maturity (SD-PM) from 33.6 to 31.8 d,
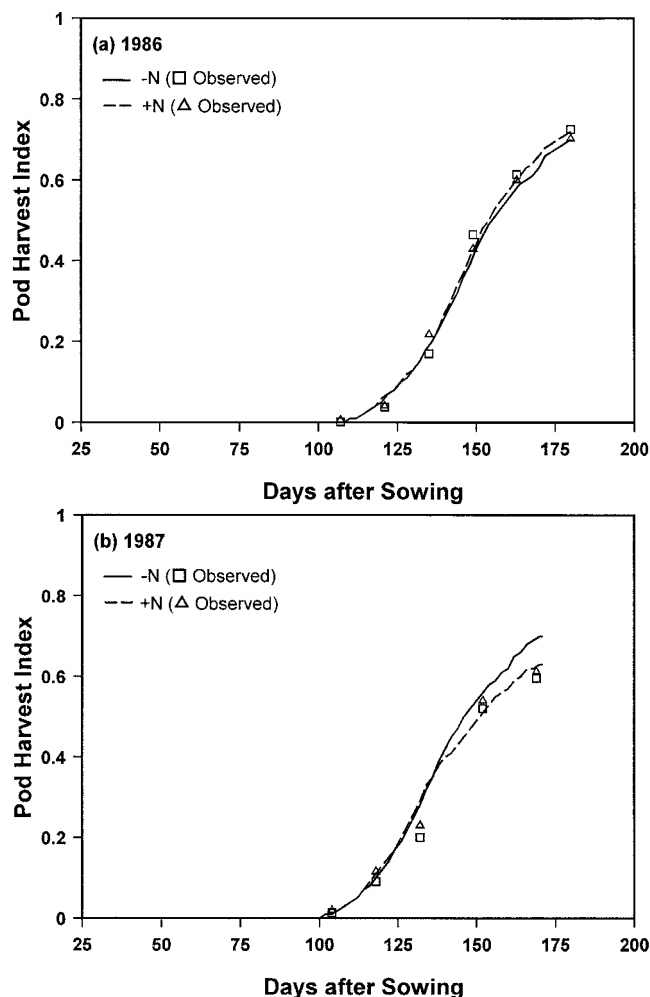

Fig. 2. A comparison of simulated (lines) and observed (symbols) pod harvest index as a function of days after sowing for faba bean cultivar Alameda grown in Cordoba, Spain, in (a) 1986 and (b) 1987. +N, fertilized uninoculated; −N, unfertilized inoculated.

Table 2] to delay the onset of rapid pod growth but maintain the same total life cycle. This shift resulted in the correct initial increase in pod mass (Fig. 1) and pod HI (Fig. 2). Pod HI, because it is a ratio not biased by randomly large or small biomass samples, is particularly valuable for setting the timing. Pod HI was well predicted, particularly with the slight early lag, the mostly linear middle phase, and the slight curvilinear phase during late pod growth (Fig. 2). Pod HI was slightly overpredicted in 1987; observed pod HI may be lower because of higher planting density in that year (Sau and Mínguez, 2000).

Partitioning of Dry Matter to Pod, Leaf, Stem, and Root

The species file contains an array function that describes the instantaneous daily partitioning among leaf, stem, and root tissues, depending on crop developmental stage (vegetative and reproductive), until addition and growth of pods and seeds become dominant in assimilate demand. Partitioning of dry matter among aboveground tissues was evaluated by comparing simu-
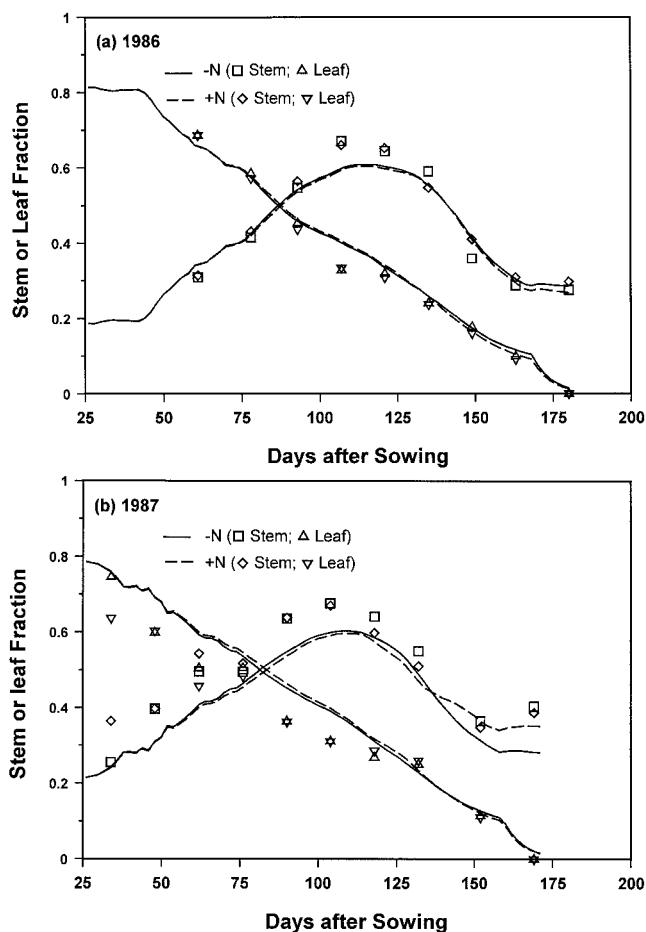
Fig. 3. A comparison of simulated (lines) and observed (symbols) fraction leaf and fraction stem as a function of days after sowing for faba bean cultivar Alameda grown in Cordoba, Spain, in (a) 1986 and (b) 1987. +N, fertilized uninoculated; −N, unfertilized inoculated.
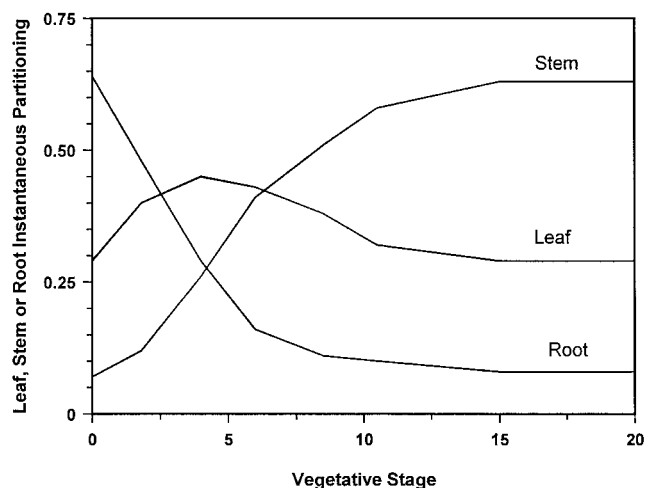

Fig. 4. Instantaneous daily partitioning of dry matter among vegetative components (leaf, stem, and root) of faba bean as a function of vegetative stage (number of main-axis nodes), after model calibration to observed fraction leaf and fraction stem shown in Fig. 3.

lated vs. observed fraction leaf, fraction stem (Fig. 3), and pod HI (Fig. 2), which are the cumulative result of daily partitioning among aboveground tissues. The original instantaneous daily partitioning function from dry bean was inadequate for faba bean, and the function was modified to better predict cumulative fractions of dry matter found in leaf and stem (Fig. 3). These modifications also improved the prediction of leaf and stem mass (data not shown). Note how the final instantaneous vegetative partitioning function (Fig. 4) has an asymptotic decline in allocation to root but a corresponding asymptotic increase in allocation to stem, as a function of main-stem node number. The function in Fig. 4 applies only to allocation among vegetative tissues. When pods and seeds are added, they have priority over this partitioning function.

In the above comparison, we did not have observed values for fraction root but compared with values published by Manschadi et al. (1998a, 1998b), who noted that apparent fraction root decreased initially from 0.60 to 0.10 by the time of rapid pod growth when root growth was essentially complete. Model predictions of apparent fraction root after calibration mostly mimic the decline in fraction root that they reported, as would

be generated by model use of the instantaneous daily partitioning function in Fig. 4. In addition, predicted root growth was compared with root mass and RLD from the literature and observed RLD data for the 1986 experiment. The predicted maximum value for root mass was 640 kg ha^{-1}, which is within the range of peak root mass of 600 to 1000 kg ha^{-1} reported by Manschadi et al. (1998a, 1998b). While the initial simulation of root mass was reasonably predicted after calibration of partitioning among leaf and stem, several minor modifications were made, primarily to RLD: (i) Rate of root senescence (RTSEN) was decreased from 0.02 to 0.01 per day because root mass and RLD showed no signs of decline in observed and literature-reported values, (ii) root length per unit root mass was increased from 7500 to 9000 cm g^{-1} because RLD was lower than reported, and (iii) the default rooting preference function for this soil was modified to slightly increase RLD in the top 15 cm and slightly decrease the value at 45- to 60-cm depth; otherwise, the rooting profile matched reasonably well the values reported by Sau and Mínguez (2000). Sau and Mínguez (2000) observed that faba bean rooted more deeply in this nonrestrictive soil than in the soils reported by Manschadi et al. (1998a, 1998b). After these changes, maximum predicted RLD was 1.2 cm cm^{-3} in the top 15 cm of soil, and peak total root length was 5.9 km m^{-2} land area, which compare with values of RLD of 1.5 to 2.0 cm cm^{-3} in the top 15 cm of soil and peak total root length of 5.6 and 7.8 km m^{-2} land area at bloom and maturity, respectively, observed in this same 1986 experiment (Sau and Mínguez, 2000). Manschadi et al. (1998a, 1998b) reported RLD of 2 to 3 cm cm^{-3} in the top 15 cm and peak total root length of 2.7 km m^{-2} land area, but their soil was shallow.

Compared with dry bean (initial default), the partitioning to leaf and stem early in the life cycle had to be decreased while partitioning to root was increased. During mid– to late life cycle, partitioning to stem was increased, and partitioning to leaf was decreased. The onset of pod and seed addition (calibrated previously

to pod HI, Fig. 2) decreases the actual partitioning to vegetative components, and thus affects the amount of stem mass produced during mid–life cycle before rapid pod growth and influences the apparent fraction stem and leaf (Fig. 3). Thus, it was important to adjust timing of pod growth before evaluating these functions. In addition, the partitioning to leaf during early season was somewhat interactive with SLA, LAI, and a model feature that sets an upper limit on early leaf area expansion for the first five nodal positions as a function of vegetative stage.

Prediction of Leaf Area Index and Specific Leaf Area

The model's ability to predict LAI (Fig. 5) depends on the ability to predict leaf mass (from daily growth and current partitioning to leaf) and SLA. Dry matter allocation to leaf mass is determined by the partitioning function modified for faba bean as previously described. The SLA of new leaves depends on environment: solar irradiance, temperature (decreased if cool), and water deficit (decreased when TURFAC is less than 1.0). For the response to light, two parameters (SLAMAX and SLAMIN) determine SLA of new leaves within poten-tial SLA limits under low or high irradiance, respectively. These two parameters were set at 900 and 325 cm^2 g^{-1}. The SLAMIN parameter basically sets the potential SLA of the species during the peak canopy LAI phase. Simulated SLA can be less than SLAMIN if there are water deficit or temperature limitations or higher if irradiance is low.

The time of peak LAI in the model is influenced by the onset of pod and seed growth, partitioning between vegetative components (leaf, stem, and root), and the time when leaf area expansion ceases. The latter is set by the variable FL-LF (Table 2), which is the PD from anthesis to end of leaf area expansion, after which any leaf mass added has SLA of zero. The FL-LF was set to 45 PD, which is about 78% of the time from anthesis to maturity. Secondary thickening is possible if assimilate is available after FL-LF. Based on our visual inspection of the Alameda cultivar, there were no immature or unexpanded leaves remaining when rapid seed growth had begun.

After model calibration, the predictions of LAI (Fig. 5) were good for the 1986 season (slightly high) but were lower than observed in the 1987 season, at least during the period of peak LAI. The observed SLA was lower in 1987 than 1986, but the model failed to predict that difference, possibly attributable to effects on SLA from higher sowing density in 1987 and/or higher temperature during the period of rapid leaf area growth (2.6°C higher Tmax during the 38-d period from anthesis to beginning seed) (Sau and Mínguez, 2000) that the model did not capture. The lower LAI predictions in 1987 may also be associated with model underprediction of total dry matter (leaf and stem as well) during the middle of the season (Fig. 1b) yet correct prediction of final biomass and grain yield. We are more confident in the final biomass and grain yield measurements (Table 3).

Leaf Senescence Relative to Mobilization of Protein and Carbohydrate during Grain Fill

The decline in stem and leaf mass during late season depends on the mobilization rate of proteins and carbo-
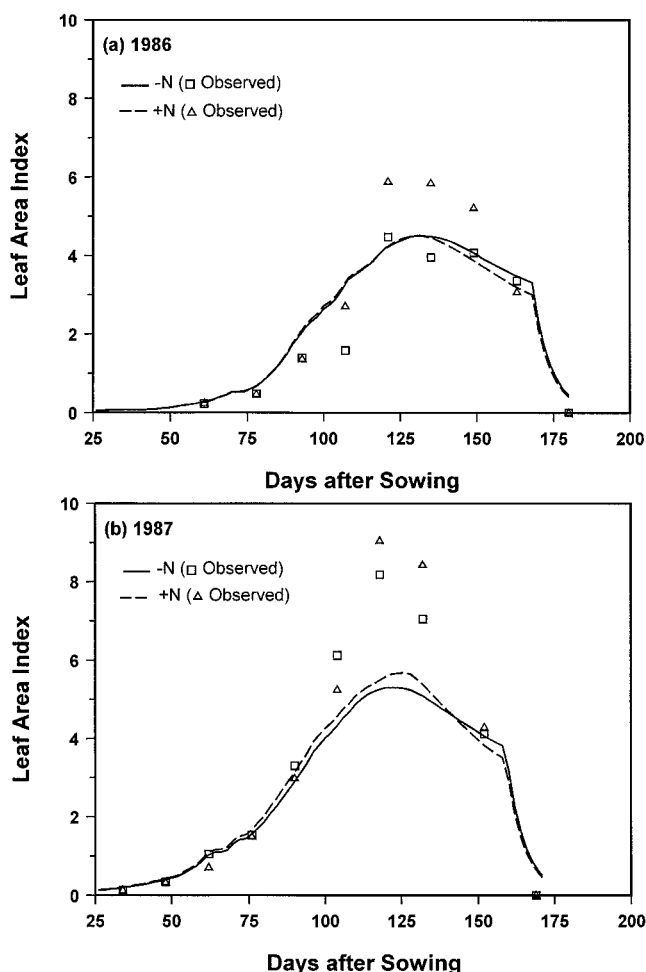

Fig. 5. A comparison of simulated (lines) and observed (symbols) leaf area index as a function of days after sowing for faba bean cultivar Alameda grown in Cordoba, Spain, in (a) 1986 and (b) 1987. +N, fertilized uninoculated; −N, unfertilized inoculated.
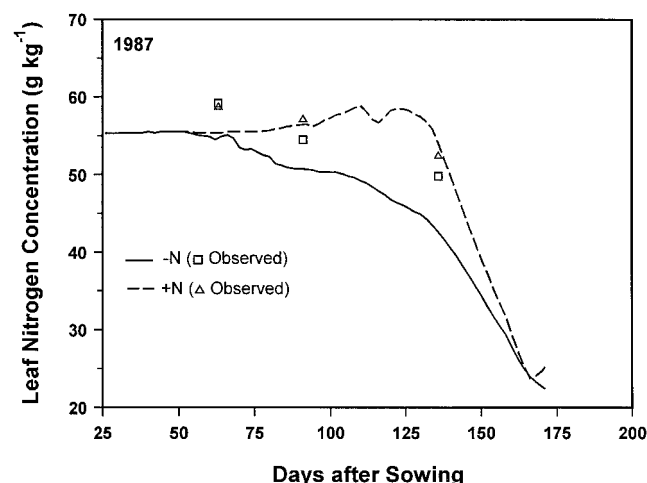

Fig. 6. A comparison of simulated (lines) and observed (symbols) leaf N concentration as a function of days after sowing for faba bean cultivar Alameda grown at Cordoba, Spain, in 1987 under two treatments (+N, fertilized and −N, unfertilized).

hydrates as well as abscission of leaf or petiole (latter from stem pool). Rate of protein mobilization was calibrated to mobilize about two-thirds of the protein from vegetative tissues by the time of maturity and to result in a final leaf N concentration of 23 g kg^{-1} (Fig. 6). The amount of nonprotein vegetative mass abscised per gram of protein mobilized (SENRTE) was decreased from 1.0 to 0.8 g g^{-1}. The value of 0.8 is also used for the soybean model. CROPGRO predicts the amount of stem mass (petioles) abscised as a fraction of the leaf mass abscised (PORPT), based on the assumption that the leaf blade has a certain mass of attached petiole that is abscised (from the stem mass pool) when the leaf is abscised. For faba bean, PORPT was set to 0.15—lower than soybean (0.58), peanut (0.21), and dry bean (0.30)—because faba bean has smaller petioles than soybean and dry bean. In addition, petioles frequently stay on the plant at maturity while the leaves turn black and fall off. Peanut is similar in this respect. Decreasing PORPT increased stem mass and lowered pod HI at maturity (both changes were needed).

Characteristics of Seed Size, Threshing Percentage, and Single Seed Fill Duration

The final mass per seed at harvest depends on genetic potential seed size (WTPSD) and environmental conditions during seed growth. The threshing percentage (seed divided by pod wall plus seed) is affected by environmental conditions, genetic potential (THRESH), and the individual seed-filling duration (SFDUR) relative to total time from the first seed to physiological maturity (SD-PM) (see Table 2 for these cultivar coefficients). Modeled seed size was calibrated to observed by setting WTPSD to 1.1 g seed^{-1}. Initially, the model underestimated the observed threshing percentage, using inputs of THRESH of 74% and SFDUR of 23 PD. The SFDUR was decreased from the initial value of 23 to 21 PD, in part, to fill seeds faster and increase the predicted threshing percentage, which the model initially underestimated. Nevertheless, the observed threshing percentage values in the 1986 and 1987 experiments were larger than values in the literature. Therefore, we set the threshing percentage based on values extracted from equations of Stutzel (1995a), which indicated observed threshing percentage of about 76% when final seed size occurred. Potential (THRESH) was increased from default of 74 to 77% to allow actual threshing percentage to approach 76%. These changes in SFDUR and THRESH caused minor effects on the required timing of FL-SH and FL-SD because they reduced allocation to pod wall. Setting some of these coefficients required some iteration with previous changes.

Simulated Growth, Nitrogen Concentration, and Nodule Mass in Response to Nitrogen Fertilization

The experiments included a comparison of a +N treatment to a −N treatment that relied mainly on N$_2$ fixation. This allowed us to evaluate the model's ability to simulate nodule growth, N$_2$ fixation, N accumulation, and N concentrations of leaves and grain. Simulations

of these treatments confirmed experimental results showing that growth, final biomass, and yield were not measurably different between +N and −N treatments. The model is configured to add and grow nodules in response to minor internal plant N deficits. There is also a feature of *bypass* carbohydrate flow to nodules irrespective of N deficit, whereby a fraction (FRCNOD = 0.055) of the assimilate allocated to roots before anthesis can be used to grow nodules even though the plant may not be experiencing N deficit. This feature was developed for soybean to prevent excessive N deficits (low leaf N concentrations and high vegetative carbohydrate concentrations) under low-N conditions. The concept of bypass flow of assimilate to start nodule growth, plus the high nodule relative growth rate, were helpful to minimize a predicted dip in early season leaf N concentration for the treatment relying on N$_2$ fixation as shown in Fig. 6 while the luxury uptake aspects allowed higher N concentration for the N-fertilized treatment. Model features that caused slightly higher yield from N-fertilized crops included: (i) lower cost to produce protein from NO$_3$ (RNO3C, 2.556 g glucose g^{-1} protein produced) compared with N$_2$ fixation (RFIXN, 2.830 g glucose g^{-1} protein produced) and (ii) luxury N uptake that pushes leaf N concentration somewhat higher than leaf N concentration of N$_2$–fixing plants, thus giving slightly higher leaf photosynthesis. The predicted seed yield averaged 6486 and 6263 kg ha^{-1} for +N vs. −N treatments, respectively (3.6% higher with N fertilization), while the observed seed yield averaged 6477 and 6177 kg ha^{-1} for +N vs. −N treatments, respectively (a 4.8% response to N fertilization). The simulated response to N fertilization was somewhat variable for treatments and years, hypothetically because different simulated dynamics of soil N mineralization, N leaching, and crop N demand may have led to different times when the crops made the transition from mineral N fed to mostly supplied by N$_2$ fixation. Indeed, the observed crop in 1987 under N fertilization had a nodule mass that was about one-half as much as the N$_2$–fixing crops, a trend that the model also predicted (Fig. 7), thus
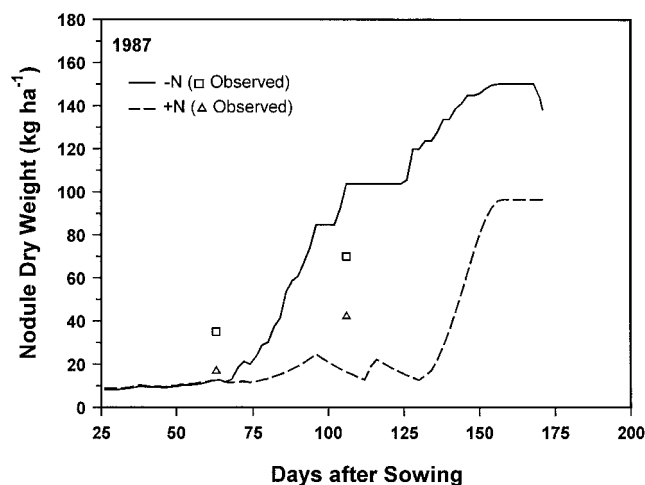

Fig. 7. A comparison of simulated (lines) and observed (symbols) nodule mass as a function of days after sowing for faba bean cultivar Alameda grown at Cordoba, Spain, in 1987 under two treatments (+N, fertilized and −N, unfertilized).

confirming that the N-fertilized crop was partly dependent on N_2 fixation. The rhizobium infecting faba bean are endemic to the location.

Model Sensitivity Analysis: Effect of Sowing Date at Three Locations

Because much of the faba bean species adaptation of CROPGRO required changing cardinal temperatures to cool-season type and a shift to long-day type, we conducted a sensitivity analysis for model response to sowing date under nonlimiting water and nutrient conditions at locations differing in temperature and latitude.

Model simulations were conducted for sowing on monthly intervals at Cordoba (Spain), Lugo (Spain), and de Bilt (the Netherlands), using 8, 15, and 15 yr of weather data, respectively. Optimum sowing dates for yield under irrigated conditions were 1 December to 1 February at Cordoba, with reasonable yield for sowing on 1 March (Fig. 8a). This conforms mostly to actual practice in the region although it is important to note that the earlier dates would normally be used under rainfed conditions to place grain fill during better rainfall and vapor pressure deficit conditions. Later sowing dates at Cordoba gave lower yields and a bimodal mini-
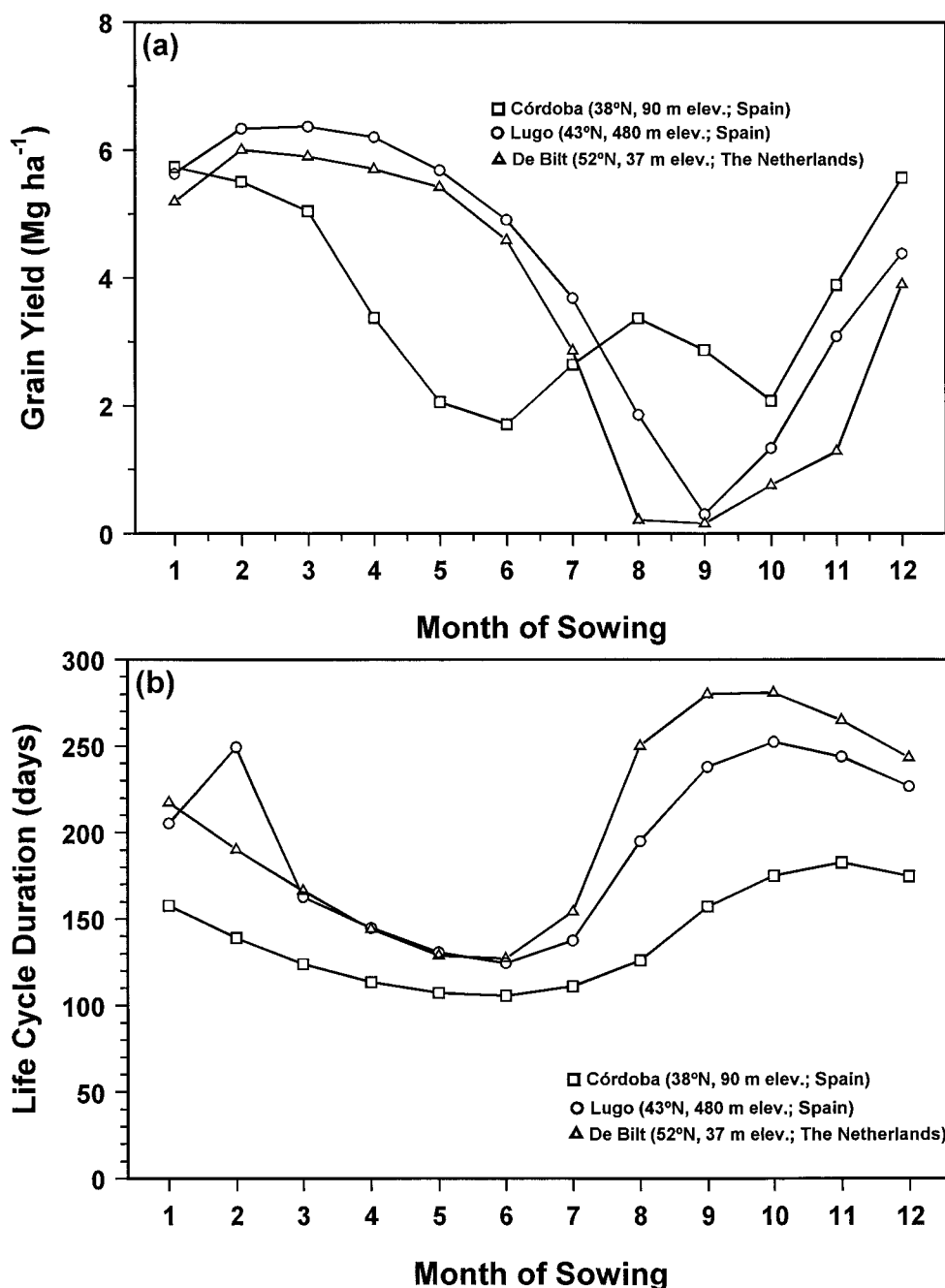

Fig. 8. Effect of sowing date on (a) simulated grain yield and (b) simulated total life cycle of faba bean cultivar Alameda grown at Cordoba, Spain; Lugo, Spain; or de Bilt, the Netherlands under nonlimiting water and nutrient conditions.

mum, associated with short life cycle (Fig. 8b) and high temperature for the first minimum and a long life cycle but cold winter temperatures during grain fill for the second minimum. Simulations at Lugo suggested high yield under irrigated conditions for sowing 1 February to 1 April, with reasonable yield for 1 January or 1 May sowing dates (Fig. 8a). Low yield was predicted for summer and early fall sowing because grain fill was placed during unfavorably cold winter and low light at that time. In addition, the August through December sowing dates at Lugo were subject to freeze-kill (lower than −8°C) for 2 of 15 yr, and January sowing had freeze-kill in 1 of 15 yr, which caused zero or very low yields. Even if the freeze years were removed and means recomputed, those sowing dates still had low yields; removing the freeze years and recomputing the means would make the January and December sowing dates move up slightly to become closer, but yields would still be below optimum. There were no freeze occurrences for the Cordoba location. The de Bilt location clearly showed an optimum sowing date for 1 February to 1 May (Fig. 8a), consistent with normal spring sowing of faba bean in that region. Freeze-kill occurred in 5, 13, 11, 11, 11, 5, and 2 of the 15 yr for sowing in July, August, September, October, November, December, and January, respectively. Removing the freeze-kill years and recomputing yield means showed the same basic yield trends although 1 December and 1 January could be high-yield sowing dates, provided the crop was immune to freeze. We conclude the faba bean adaptation of CROPGRO gives reasonable behavior in these sowing date responses under nonlimiting water conditions; however, the model should not be applied too far from these conditions until further tested under diverse weather, particularly drought conditions, and for different cultivar types.

What was Learned about the Adaptation Process?

There were advantages in adapting an existing mechanistic model such as CROPGRO because the model already describes many basic processes of photosynthesis, respiration, N_2 fixation, plant N and C balance, and soil water and N balance. Despite their apparent complexity, most of these plant processes are quite conserved (repeated), and thus seemed to be predicted as well for faba bean as they had for the three other grain legumes previously modeled by CROPGRO. Thus, lack of specific literature information on these processes for faba bean was not a problem. Rather, we learned that the more important aspects for adapting CROPGRO to faba bean were associated with changing cardinal temperatures of the processes to cool-season species traits, shifting to long-day sensitivities, and obtaining cultivar attributes for timing of anthesis, reproductive partitioning, and maturity. For this reason, we are able to start with processes well simulated for other legume crops and modify their temperature sensitivities, based substantially on literature information for faba bean or by analogy to other processes or contrast to other spe-

cies where literature information was lacking. Table 1 summarizes those cardinal temperature sensitivities (part of the species traits) for faba bean by comparison to soybean, a warm-season grain legume. Notice that both Tb and Topt of faba bean are about 4 to 8°C below corresponding values for soybean. The adaptation process also involved developing some relationships and parameters by comparison to observed experiments. Some of these traits are also cultivar traits (Table 2). We believe the faba bean model to be well grounded in physiological principles and presently appropriate for limited use under nonlimiting water conditions. Sensitivity analyses showed reasonable simulated responses to sowing date at three latitudes that were typical of a cool-season, long-day crop.

Future Release of CROPGRO Faba Bean as Part of DSSAT–ICASA System

The CROPGRO model version for faba bean will be included in the DSSAT package of crop models and will be available as part of the next released version. The faba bean model version uses the standard CROPGRO model (FORTRAN code is unchanged) but requires the new species, ecotype, and cultivar files (named *.SPE, *.ECO, and *.CUL) developed here. The model uses the standard input–output conventions of the DSSAT system, using the standard weather and soil files, and graphics outputs. As for most crop models, the faba bean version should be tested more widely for other cultivars, locations, and weather situations to determine how robust the model version is for diverse environments. Release within the DSSAT package will make it available for such testing.

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