

Predicting growth and development of pigeonpea: a simulation model

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Abstract

A simulation model of pigeonpea is described that is designed to simulate the development, growth, nitrogen accumulation and yield of a wide range of maturity types from extra-short to medium-duration in response to weather, soil conditions and agronomic management. Parameters of the model for phenological development, leaf area expansion, radiation interception, biomass accumulation and partitioning, crop water use, root growth and water extraction, and nitrogen accumulation are derived from published studies. In addition, the calibration exercise is described to derive the parameters accounting for the effect of plant population density on leaf area expansion. The model was tested on 38 data sets, not previously used to derive model parameters, collected at Patancheru, India. Data sets encompassed a wide range of plant type, sowing density, and seasons, grown on alfisol and vertisol soil types under dryland and irrigated conditions. The time to flowering and maturity from the extra-short to medium-duration types were simulated well, explaining 96 and 92% of the variance (RMSD = 4.3 and 9.8 days), respectively. Total aboveground biomass was simulated with less accuracy, explaining 74% of the variance (RMSD = 2056 kg ha⁻¹) and grain yield was simulated explaining 76% of the variance (RMSD = 332 kg ha⁻¹). There remains scope for model improvement in the areas of waterlogging and testing on crop N accumulation. This pigeonpea module, when coupled with other crop, soil and management modules can be used to address a range of cropping systems issues. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) plays a major role in the household economy of farmers in the tropics and subtropics. Apart from its dietary benefits,

pigeonpea has long been recognised for its attributes of high leaf-fall and the consequent contribution to the carbon and nitrogen economy of the soil (Rego and Nageswara Rao, 2000). The availability of new short and extra-short duration cultivars with wide adaptation, and hybrids, makes it possible to grow pigeonpea as a sole crop, and also in rotation with winter crops in areas where pigeonpea is not traditionally cultivated (Laxman Singh et al., 1996). This opens up new management opportunities and complexities of water and nitrogen availability that are difficult to address through classical agronomic experiments.

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The development and application of simulation models of crops is well established in studying crop response to changes in cultivar, soil, weather, climatic patterns and management practices (Penning de Vries, 1977; Monteith and Virmani, 1991). To our knowledge there is no crop simulation model for pigeonpea. This paper describes a model of pigeonpea with the capacity to simulate the range of cultivar types from extra-short to medium-duration phenology in response to weather, soil conditions and agronomic management.

2. Model description

2.1. Structure and overview

The pigeonpea model is a module of APSIM (agricultural production systems simulator) (McCown et al., 1996). APSIM allows models of crop and pasture production, residue decomposition, soil water and nutrient flow to be readily configured to simulate various production systems, including crop sequences and intercropping, and soil and crop management to be dynamically simulated using conditional rules.

Pigeonpea is also a part of a wider group of legume species simulated by a generic crop simulation template, and the reader is referred to Robertson et al. (2001b) for a fuller description of the approach. The pigeonpea module simulates crop development, growth, yield and nitrogen accumulation in response to temperature, photoperiod, soil water and nitrogen supply. The model uses a daily time-step, and is designed to simulate a uniform field and predict grain yield, crop biomass, crop nitrogen uptake (including fixation) and partitioning within the crop. Different cultivars are defined in the model in terms of phenological development and partitioning of biomass to grain.

The parameters and relationships needed to build the functions in the model were derived from a number of sources (e.g. Carberry et al., 2001; Ranganathan et al., 2001; Robertson et al., 2001a).

2.2. Phenology

Progression through phenological phases signals changes in the growth and partitioning of biomass

between roots and aboveground parts, including grain. It is simulated from sowing through 10 stages: (1) sowing, (2) germination, (3) emergence, (4) end of juvenile stage, (5) floral initiation, (6) flowering, (7) start of grain fill, (8) end of grain fill, (9) maturity, (10) harvest ripe.

Achievement of each stage is simulated when a predetermined number of thermal units are accumulated. Germination is set to occur the day after sowing. For emergence, 18.0°C day is required plus 1.4°C day mm⁻¹ of sowing depth. The thermal time from the end of juvenile stage to floral initiation is determined by photoperiod. Pigeonpea is a short-day plant and when the plant experiences photoperiods beyond a critical value, progression to flowering ceases (i.e. a qualitative response) (Carberry et al., 2001). It is only when the photoperiod returns below this critical value that progression to flowering continues.

Thermal time is calculated using a “broken-stick” function with three cardinal temperatures: base (10°C), optimum (32°C), and maximum (45°C) (Carberry et al., 2001). Daily thermal time (in degree days) is calculated from three-hourly air temperatures interpolated from the daily maximum and minimum temperatures. These daily values are accumulated into a thermal time sum used to determine the duration of each phase.

Pigeonpea cultivars are grouped at Patancheru, India, a low-latitude tropical environment (Sharma et al., 1981), into maturity classes of extra-short, short, medium and long on the basis of the number of days to flowering. For the purposes of model parameterisation, three duration groups were specified: extra-short, short and medium. There is a lack of detailed information on which to develop parameters for the long-duration group. Table 1 lists the cultivar parameters for each class.

The rate of phenological development may be increased or decreased under water or nitrogen deficit. Such differences in phenology could be simulated with the current model framework, but there is a lack of published information enabling the functional relationships to be parameterised.

2.3. Leaf area development

Leaf area development is described using functions for the appearance, expansion and senescence of

Table 1

Pigeonpea parameters for the three cultivar-types with an example cultivar name given. Parameters are derived from Carberry et al. (2001) and Robertson et al. (2001a)

Parameter description	Units	Cultivar type																	
		Extra-short (e.g. cv. ICPL 84023)					Short (e.g. cv. ICPL 87)					Medium (e.g. cv. ST1)							
Daily potential increase in HI	per day	0.0085					0.0075					0.0040							
Maximum HI		0.40					0.35					0.20							
Lookup table for photoperiod and thermal time from end juvenile to floral initiation	h vs. °C day	12.8	13.5	13.6			12.8	13.5	13.6			11.4	13.2	13.3					
		0	7	10000			0	630	10000			0	1650	100000					
Thermal time from floral initiation to flowering	°C day	10					10					203							
Thermal time from flowering to start of grain fill	°C day	50					100					150							
Thermal time from flowering to maturity	°C day	650					600					680							
Thermal time from maturity to harvest ripe	°C day	36					36					36							
Lookup table for stem weight per plant and plant height	g vs. cm	0	4	9	25	85	130	0	4	9	25	85	130	0	4	9	25	85	130
		0	60	100	130	200	210	0	60	100	130	200	210	0	60	100	130	200	210

leaves. Node and leaf appearance can occur from emergence until maturity, depending upon the supply of assimilate available for leaf growth. Appearance of fully expanded leaves is determined from the rate of node appearance on the main stem, taken from Ranganathan et al. (2001) as 33°C day per node, and the potential number of fully expanded leaves per mainstem node, taken as 10 leaves after the appearance of node 15 (Ranganathan et al., 2001). At emergence, leaf area is assumed an initial value (1300 mm² per plant). Potential leaf area expansion is the product of the rate of appearance of fully expanded leaves and the maximum size of leaves. Maximum leaf size was derived as a function of node number from Ranganathan et al. (2001), where leaf size increases linearly from 700 mm² at node 1 to 2844 mm² at node 45.

In the absence of water or N stress, actual leaf area production (determined by temperature), if carbon supply is limited, may be less than potential leaf area expansion as is set by a maximum specific leaf area for the daily increase (SLA_{max}). Carbon supply may become limiting, for example, at high plant population density or low incident radiation. As SLA_{max} places a constraint on the daily increase in leaf area it is not readily derived from experimental data and must be calibrated by trial and error.

In order to provide data to calibrate the model for density effects on leaf area expansion, leaf area index was measured in an experiment, which had a range of plant population density. The extra-short duration cultivar ICPL 88039 was sown on 23 June 1997 at 4, 8, 17 and 33 plants m⁻² with 60 cm row spacing, at ICRISAT Asia Centre, Patancheru, India (latitude 17°31'N, longitude 78°16'E; elevation 530 m). The plots, which measured 9 m × 6 m, were replicated three times. The soil type was an alfisol (a clayey skeletal, mixed iso-hyperthermic, udic rhodustalf). A basal application of di-ammonium phosphate (18% N, 20% P) at 100 kg ha⁻¹ was applied. Seeds were treated with thiram and metalaxyl before sowing to control soil-borne fungal diseases. Sowing was on ridges 60 cm apart. Two seeds per hill were sown and plants were thinned to one per hill at 20 days after sowing to provide the target plant population density. Plots were weeded manually at regular intervals in the early growth stages until the canopy closed. Insecticides (endosulphan or methomyl) were used at frequent intervals, starting from the time of flowering, to

control insect pest damage, especially that caused by *Helicoverpa armigera* and *Maruca testulalis*. Irrigation was applied every 3–5 days depending on the dryness of the soil surface at a rate equal to pan evaporation. Meteorological data including maximum and minimum air temperature, and incident radiation were recorded daily. Every 7–14 days, green leaf area index (LAI) was determined by sampling three adjacent plants in each plot, and separating plants into dead and green leaves, stems, pods, and flowers, and drying at 70°C for 48 h to determine dry weight. Leaf litter was not recovered. Leaf area of harvested plants was determined by using an automatic leaf area meter (Delta-T Devices, Cambridge, UK).

Fig. 1 shows the results from the calibration exercise for the population density experiment. As a first step, the model is run with SLA_{max} unconstrained (600 cm² g⁻¹), with the result that a large number of leaves is produced, the specific leaf area of the canopy is high (i.e. leaves become very thin) because carbon is not constraining leaf area expansion, and, consequently, LAI is over-predicted, especially in the high density treatment. The next step in calibration is to progressively reduce the value of SLA_{max}, so that carbon supply becomes progressively more limiting to expansion, until the simulated canopy specific leaf area and LAI matches the observed (Fig. 1). The SLA_{max} that best fits LAI and SLA of the whole canopy across the range of densities is then used in the model, in this case 400 cm² g⁻¹.

Leaf senescence is simulated as a function of thermal time after flowering as described by Ranganathan et al. (2001). Every 34°C day, a fraction of the total plant leaf number (0.029) senesces. The rate of leaf senescence may be enhanced in dense canopies (light competition), under drought conditions, and with the occurrence of frost.

2.4. Biomass accumulation and partitioning

The proportion of radiation intercepted by the crop canopy in relation to LAI is defined by the radiation extinction coefficient (k) derived to be 0.53 by Robertson et al. (2001a) from studies at a row spacing of 60 cm. We make corrections to k based on row spacing and arrangement because it is known to respond in this way in other species (e.g. Flenet et al., 1996). Information on the response of k to

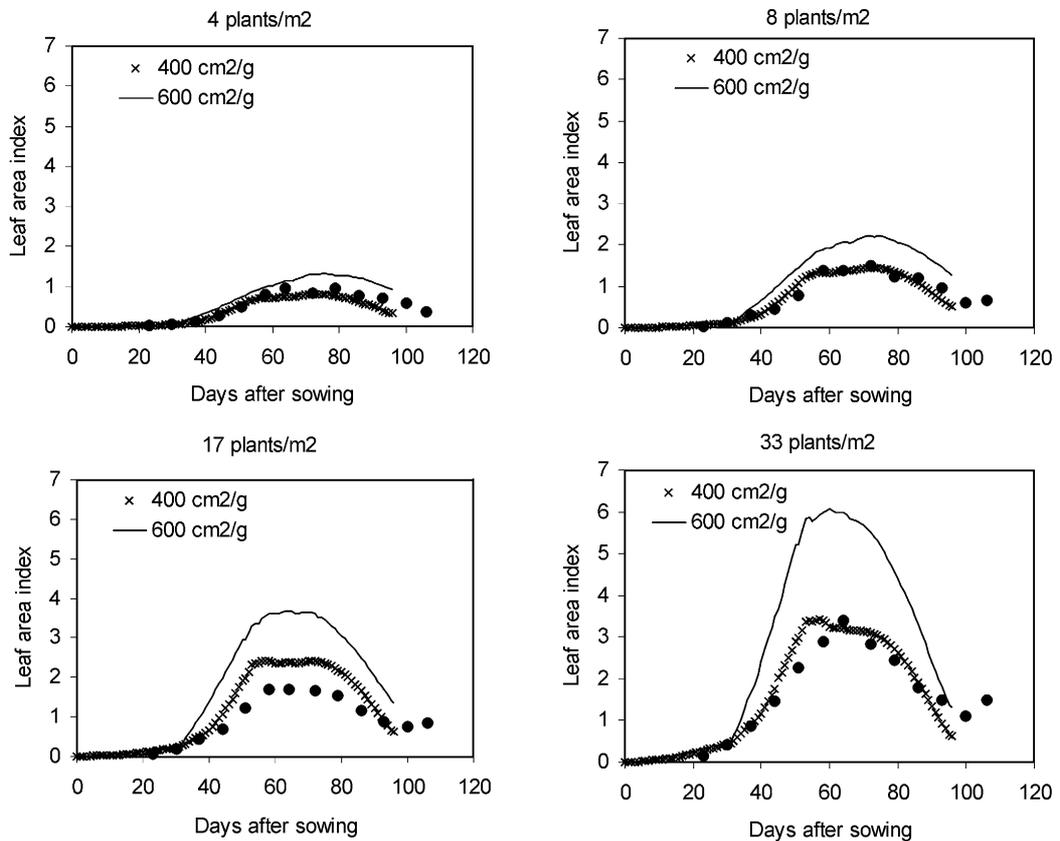


Fig. 1. Calibration of the model parameter maximum specific leaf area for daily leaf area increase (SLA_{max}). Points are observed LAI and lines are simulated LAI without assimilate constraints on leaf area expansion (SLA_{max} = 600 cm² g⁻¹), and calibrated values (SLA_{max} = 400 cm² g⁻¹).

row spacing in pigeonpea is unavailable, so the general shape of the function of Flenet et al. (1996) for soybean is used. Here, k is set to decline from 0.8 to 0.65 to 0.4 at row spacings of 0.2, 0.5 and 1.0 m, respectively. Intermediate values are derived by linear interpolation. The response curve developed by Flenet et al. (1996) is an approximation to deal with the hedgerow structure that generates incomplete canopy cover. Its use here may be limited in its applicability to a wide range of situations, because the value of k should be sensitive to seasonal LAI variations at a fixed row spacing. As extra-short duration cultivars vary in LAI up to 3, short duration up to 4, and medium-duration up to 6 (Robertson et al., 2001a), the approach of varying k with row spacing may be limited in applicability across the range of maturity types and population densities at which they are grown. It is possible that a more rigorous

treatment of radiation interception by row crops is required, along the lines of that used by Boote et al. (1992), however, this awaits detailed data for seasonal variations in radiation interception and LAI at a range of row spacings.

Potential aboveground biomass production is predicted from LAI, k and the crop radiation-use efficiency (RUE). The value of RUE, 0.9 g MJ⁻¹, is taken from Robertson et al. (2001a). RUE can be limited by sub-optimal or supra-optimal average daily temperature. The cardinal temperatures for this relationship are best derived from measurements of photosynthetic rate as a function of temperature, but this information is not available for pigeonpea. Here, RUE is assumed to be reduced linearly when the mean daily temperature is between 0 and 20°C and between 35 and 45°C, respectively. These cardinal temperatures need

verification, especially when the crop is grown during the cool season (rabi season in India or at high altitudes in Africa).

Actual daily biomass increase is calculated from the minimum of two potential crop growth rates, one determined by the intercepted radiation, limited by temperature and nitrogen stresses, and the other by soil water supply.

Daily-synthesised biomass is partitioned to roots, leaf, stem, pod wall and grain. Between emergence and flowering 0.45 of biomass produced is partitioned to leaf and the remainder to stem (Robertson et al., 2001a). However, if the amount of carbon partitioned to leaf is more than required for the calculated increase in leaf area (the leaves have a maximum thickness) then the residual is partitioned to stem. The minimum value of specific leaf area is assumed to be $80 \text{ cm}^2 \text{ g}^{-1}$. Likewise if the carbon partitioned to leaf is insufficient for the potential increase in leaf area, leaf area increase is reduced (see leaf area development section).

Between flowering and start of grain fill, 0.10 of biomass is partitioned to leaf. Of the carbon remaining after leaf demand has been satisfied, a proportion goes to pod wall (0.15) and the remainder to stem. Between the start of grain fill and maturity, biomass is partitioned, in order of priority, between grain plus pod wall, and stem plus leaf. Partitioning to grain depends on calculated grain demand. The pod wall accounts for a fraction of the grain demand (0.50). If there is biomass remaining after grain demand has been satisfied, 0.10 goes to leaf, and the remainder going to stem. New leaf area may be produced in this way, if there is low demand for assimilate by grain during grain fill. Grain demand for assimilate is driven using a cultivar-specific daily rate of harvest index (HI) increase up to a genetic maximum. Spaeth and Sinclair (1985) were the first to note the constancy of the increase in HI during grain fill in soybean, and Robertson et al. (2001a) have shown it applies also to pigeonpea. In the model, the daily increase in HI is used to calculate the demand for assimilate, which commences at the start of grain fill (Table 1). In some situations, assimilate supply may be inadequate to meet demand, so the realised daily increase in HI may not necessarily be equal to the potential. The genetic maximum HI effectively places an upper limit on the duration of grain fill (Table 1). The potential daily increase in HI is cultivar-specific (Table 1) to

account for known variation within the main cultivar groups in pigeonpea (Robertson et al., 2001a).

The ability to meet potential grain yield is determined by the rate of biomass accumulation and the translocation of dry matter accumulated in the leaves and stems before the start of grain fill. If assimilate supply exceeds grain growth requirements, the excess is used for new leaf and stem growth. There is little data available for pigeonpea to estimate the fraction of leaf and stem dry weight available for translocation to grain. In the absence of better information, the fraction of stem and leaf biomass at the start of grain fill that can be used for translocation was assumed to be 0.3 and 0.1, respectively.

The differences in partitioning in determinate and indeterminate cultivars are small and represent morphological variation in terms of plant height and flowering pattern rather than true physiological variants (Sheldrake, 1984). Here, the same partitioning parameters are used for both types.

Plant height is needed in the pigeonpea model to simulate competition for light with companion crops in intercropping (Keating and Carberry, 1993). There are, within cultivar-duration groups (extra-short, short, medium), consistent relationships between stem mass and plant height through plant development, and across a range of plant population densities (Y.S. Chauhan and S. Silim, unpubl.). This approach is extended here to a common relationship between stem mass and height in sole-crop and intercrops, and with various plant arrangements. This assumption needs verification before the model can be applied with confidence to intercropping situations.

2.5. *Plant nitrogen relations*

Soil nitrogen transformations and movement is simulated by other modules in APSIM (Probert et al., 1997). Plant demand, uptake and translocation of nitrogen as simulated in the model are described by Robertson et al. (2001b). Briefly, the crop has defined minimum, critical and maximum N concentrations for each plant part. Demand for nitrogen is that required to maintain nitrogen above the critical (non-stressed) level. If nitrogen demand cannot be satisfied by mass flow then it is supplied by either active uptake or N fixation. There is currently no method to estimate values of the minimum, critical and maximum N

concentrations for each plant part during crop development. In this case the minimum N concentration was assumed equal to the N content of plant parts at senescence (Sanetra et al., 1998) and the critical N concentrations were taken from studies of plants nodulated and therefore apparently well-supplied with N (Sheldrake and Narayanan, 1979).

The potential daily rate of nitrogen fixation is a function of crop biomass, discounted for soil water stress, following the approach of Sinclair (1986). Kumar Rao and Dart (1987) showed a correlation between nodule number and crop size. In the model, the potential daily rate of N fixation may vary with phenological stage, in order to account for low N-fixing capacity as nodules establish early in growth, and also as nodules senesce during pod-filling (Kumar Rao and Dart, 1987). No attempt is made here to derive definitive values for the N fixation parameters, which were not the focus of model testing in this paper.

2.6. Root growth and development and soil water extraction

Roots are grown daily in a fixed proportion to the production of tops. This proportion is specified for each phenological stage, 1.0 at emergence, 0.25 at the end of the juvenile stage, 0.2 at flowering, and 0.1 at the end of grain fill. This results in root:shoot ratios at harvest in the range 0.1–0.3, which is consistent with a review of root studies in pigeonpea conducted by Lawn and Troedson (1990). The depth of rooting is simulated with a potential elongation rate of 11 mm per day from emergence until the start of grain fill (Devi et al., 1996). A root exploration factor (range 0–1), for each soil layer, constrains root elongation rate if soil properties, such as compaction or pH, are known to limit root penetration. This feature of the model is designed to account for variation in extraction front velocity with soil type (Squire, 1990, p. 124). Root biomass is converted to root length via a specific root length, taken as 8000 mm g⁻¹ (Devi et al., 1996). Root length is used in water and solute balance calculations.

2.7. Effects of water deficit

Soil water infiltration and redistribution, evaporation and drainage are simulated as described by Probert et al. (1997).

Water stress reduces the rate of leaf area expansion and RUE via a soil water deficit factors which varies from 0 to 1.0 and is calculated as a function of the ratio of potential soil water supply from the root system and the transpiration demand. Leaf expansion is more sensitive to soil drying than photosynthesis. Following Sinclair (1986) and Monteith (1986), transpiration demand is modelled as a function of the current day's crop growth rate, divided by the transpiration-use efficiency. Transpiration efficiency varies inversely with VPD. The value of transpiration efficiency at 1 kPa VPD, the transpiration efficiency coefficient, has not been determined for pigeonpea, but it is probably safe to assume that it will be similar to that for other tropical legumes (Robertson et al., 2001b), viz. around 5 g kg⁻¹ kPa⁻¹. In the model VPD is estimated using the method proposed by Tanner and Sinclair (1983).

Methods for calculating soil water uptake by the root system are described by Robertson et al. (2001b). In the model, dry soil can reduce the potential rate of N fixation. This stress differs from those for photosynthesis and expansion, by being based on the fraction of available soil water in the root zone, rather than the ratio of soil water supply to demand. Sinclair et al. (1987) related N fixation rate to the fraction of available soil water, and used this functional relationship to simulate nitrogen accumulation by soybean, cowpea and black gram in the field. Unpublished work from this same laboratory (Dr. Rachid Serraj, Laboratoire de Physiologie Vegetale, University of Marrakech, Morocco) has indicated that the sensitivity of N fixation to soil water content in pigeonpea is intermediate to that of peanut (tolerant) and soybean (sensitive). Hence, N fixation was parameterised to decline when the fraction of available soil water in the root zone fell below 0.5, halfway between the known thresholds for peanut and soybean (Sinclair and Serraj, 1995).

3. Model evaluation

3.1. Methods

3.1.1. Data sets

Data used for model evaluation were independent from those used to derive model parameters. Data (38 crops) were obtained from published and unpublished

field experiments from Patancheru, India (Table 2). Briefly, the data comprise experimental treatments with various cultivars (extra-short, short and medium-duration), soil water conditions (irrigated and

dryland), soil type (alfisol and vertisol), and plant population density.

A range of variables was measured in these experiments at varying frequency during the growing season.

Table 2

List of pigeonpea cultivars with their date of sowing (day of year), soil type (alfisol [A] or vertisol [V]), water regime (irrigated [I] or rainfed [R]), and plant density used to test the performance of the pigeonpea simulation model^a

Cultivar	Year	Sowing date	Soil type	Irrigated or rainfed	Plant density (m ⁻²)	Additional variables measured ^a	Reference
<i>Extra-short duration cultivars</i>							
ICPL 84023	1990	184	A	R	33.3	LAI, node number	Y.S. Chauhan and S. Silim, unpubl.
ICPL 83015	1990	184	A	R	33.3	LAI	S. Silim, unpubl.
ICPL 84023	1993	170	A	I	33.3	LAI, biomass components	Y.S. Chauhan and S. Silim, unpubl.
ICPL 84023	1994	172	A	I	33.3	LAI, node number	Y.S. Chauhan and S. Silim, unpubl.
ICPL 84023	1994	172	A	R	33.3	LAI	Y.S. Chauhan and S. Silim, unpubl.
ICPL 84023	1996	175	A	I	33.3	LAI, biomass components	Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1997	172	A	I	4.4		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1997	172	A	I	8		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1997	172	A	I	16.7		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1997	172	A	I	33.3		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1999	189	A	R	4.4		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1999	189	A	R	8		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1999	189	A	R	16.7		Y.S. Chauhan and S. Silim, unpubl.
ICPL 88039	1999	189	A	R	33.3		Y.S. Chauhan and S. Silim, unpubl.
<i>Short-duration cultivars</i>							
Pusa Ageti	1974	177	V	R	4.4	LAI, node number, biomass components	Sheldrake and Narayanan, 1979
T21	1974	177	V	R	4.4	LAI, node number, biomass components	Sheldrake and Narayanan, 1979
ICPL 87	1986	190	A	I	66.7		Y.S. Chauhan and S. Silim, unpubl.
ICPL 87	1986	190	A	I	33.3		Y.S. Chauhan and S. Silim, unpubl.
ICPL 87	1986	190	A	I	16.7		Y.S. Chauhan and S. Silim, unpubl.
UPAS 120	1990	184	A	R	33.3	LAI, node number, biomass components	S. Silim, unpubl.
ICPL 87	1990	184	A	R	33.3	LAI, node number, biomass components	S. Silim, unpubl.
ICPL 87	1993	170	A	I	33.3	LAI, biomass components	Y.S. Chauhan and S. Silim, unpubl.
ICPL 87	1994	172	A	I	33.3		Y.S. Chauhan and S. Silim, unpubl.
ICPL 87	1994	172	A	R	33.3		Y.S. Chauhan and S. Silim, unpubl.
ICPL 4	1996	175	A	I	33.3		Y.S. Chauhan and S. Silim, unpubl.
<i>Medium-duration cultivars</i>							
ST1	1974	185	V	R	4.4	LAI, node number, biomass components	Sheldrake and Narayanan, 1979
ICP 16	1974	185	A	R	4.4	LAI, node number, biomass components	Sheldrake and Narayanan, 1979
C11	1979	303	V	R	33.3	LAI, biomass components	ICRISAT, unpubl.
C11	1981	169	V	I	5.0	LAI, biomass components	ICRISAT, unpubl.
C11	1981	169	V	R	5.0	LAI, biomass components	ICRISAT, unpubl.
C11	1981	290	V	I	33.3	LAI, biomass components	
C11	1981	290	V	R	33.3	LAI, biomass components	
ICP 16	1990	184	A	R	6.7	LAI, node number, biomass components	S. Silim, unpubl.
ICP 16	1991	173	A	I	6.7	LAI, node number, biomass components	
ICP 16	1991	173	A	R	6.7	LAI, node number, biomass components	
ICP 16	1993	170	A	I	33.3		
ICP 16	1994	172	A	I	8.3	LAI, node number	
ICP 16	1994	172	A	R	8.3	LAI, node number	

^a In addition to dates of flowering and maturity, and biomass and grain yield at maturity.

Table 3

Layer soil type parameters used by APSIM–SOILWAT module for the two soil types: soil water contents at air dry (air dry), 1.5 MPa tension (LL15), the lower limit of plant water extraction (LL), the drained upper limit (DUL) and saturation (SAT); bulk density (BD) and the daily drainage coefficient (SWCON)

<i>Alfisol</i>										
Depth (cm)	0–15	15–30	30–45	45–60	60–75	75–90	90–105	105–120	120–135	135–150
AIR_DRY (cm cm ⁻¹)	0.050	0.135	0.220	0.230	0.230	0.230	0.236	0.233	0.231	0.231
LL15 (cm cm ⁻¹)	0.146	0.207	0.220	0.230	0.230	0.230	0.236	0.233	0.231	0.231
DUL (cm cm ⁻¹)	0.282	0.327	0.354	0.354	0.341	0.341	0.325	0.325	0.325	0.325
SAT (cm cm ⁻¹)	0.443	0.404	0.404	0.404	0.391	0.391	0.375	0.375	0.375	0.375
BD (g cm ⁻³)	1.475	1.520	1.46	1.46	1.42	1.42	1.46	1.46	1.50	1.50
SWCON	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
<i>Vertisol</i>										
Depth (cm)	0–15	15–30	30–60	60–90	90–120	120–150	150–180			
AIR_DRY (cm cm ⁻¹)	0.100	0.200	0.246	0.246	0.247	0.256	0.256			
LL15 (cm cm ⁻¹)	0.224	0.245	0.246	0.246	0.247	0.256	0.256			
DUL (cm cm ⁻¹)	0.390	0.417	0.417	0.401	0.403	0.430	0.430			
SAT (cm cm ⁻¹)	0.440	0.467	0.467	0.451	0.453	0.480	0.480			
BD (g cm ⁻³)	1.20	1.20	1.20	1.20	1.20	1.20	1.20			
SWCON	0.1	0.1	0.1	0.1	0.1	0.1	0.1			

In 24 cases, dates of 50% flowering and physiological maturity were recorded. Some data sets had further measurements of LAI, biomass components, node and leaf numbers.

In simulations reported in this paper, the pigeonpea crop module was linked with the soil water module SOILWAT (Probert et al., 1997), the soil nitrogen module SOILN (Probert et al., 1997), and the surface residue module RESIDUE (Probert et al., 1997). Two soil types, an alfisol and a vertisol, were parameterised based on soil descriptions of El-Swaify et al. (1985) and unpublished data from ICRISAT (J.P. Dimes, pers. comm.) (Tables 3 and 4). The parameters, as defined by Probert et al. (1997), consist of by layer, soil water contents at air dry, 1.5 MPa tension, the lower limit of plant water extraction, the drained upper limit and saturation. Other layer parameters are bulk density and the daily drainage coefficient. Parameters controlling soil radiation reflection, soil evaporation, unsaturated water movement between soil layers and runoff are listed in Table 4 for each soil type.

3.1.2. Initial conditions

Simulations were made for each treatment initialised according to the recorded description of each treatment. Where records were not available, estimates from nearby experiments were used. Where soil water contents could not be estimated from nearby fields, plant

extractable water was set to 10% for all soil layers at sowing. For irrigated experiments that did not specify the amount or frequency of irrigation, the model was programmed to irrigate to maintain plant extractable water greater than 70% in the top 1 m of the soil profile. The initial soil organic carbon and nitrogen were based upon measurements from nearby experiments with estimates made for the proportions of organic matter as fresh, microbial and humic carbon. The estimates are typical for these soils (Probert et al., 1997) and are not expected to cause significant bias, because the crops were well-nodulated and hence unlikely to be nitrogen limited. Residues were manually removed in all experiments, so initial surface residues were set to zero.

Table 4

Profile soil type parameters used by APSIM–SOILWAT module for the two soil types: soil radiation reflection (SALB), soil evaporation (CONA, *U*), unsaturated water movement between soil layers (DIFFUS_SLOPE, DIFFUS_CONST) and runoff (CN_BARE)

Variable	Alfisol	Vertisol
<i>U</i> (mm)	6.6	6.0
CONA	1.5	3.5
SALB	0.13	0.05
DIFFUS_CONST	250	40
DIFFUS_SLOPE	22	16
CN_BARE	85	73

Daily meteorological observations of maximum and minimum screen air temperature (°C), rainfall (mm) and total solar radiation (MJ m⁻²) were recorded at the site for the period of the experiments (1974–1997).

3.1.3. Statistical analyses

Comparisons were made between the simulated (*Y*) and observed (*X*) data with regression analyses of the form $Y = a + bX$. Measures of accuracy were made with the adjusted coefficient of determination (*R*²) and the root mean-squared deviation of between simulated and observed.

3.2. Phenology

Of the 38 independent data sets used for model testing, 24 had recorded dates of flowering and phy-

siological maturity. Fig. 2 shows the good agreement between observed and simulated days to flowering and days to physiological maturity, with RMSD values being 4.3 and 9.8 days, and the coefficient of determination of 96 and 92% for flowering and maturity, respectively. The time to maturity was simulated with less accuracy than flowering, possibly reflecting the additive effect of errors in simulating the intermediate flowering and grain fill stages. Also, in pigeonpea, it is difficult to determine physiological maturity the field due to the occurrence of multiple flushes of pods.

3.3. Leaf area index, biomass and yield

Examples of the time-course of simulated and observed growth attributes of crops of extra-short, short and medium-duration cultivars, are given in

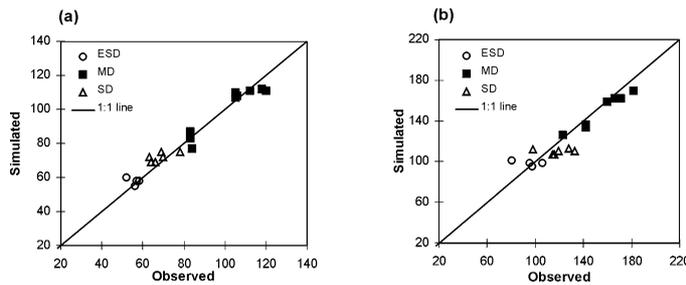


Fig. 2. Observed and simulated: (a) days to first flower, and (b) days to physiological maturity. ESD: extra-short duration cultivars, SD: short-duration cultivars, M: medium-duration cultivars. The 1:1 line is shown.

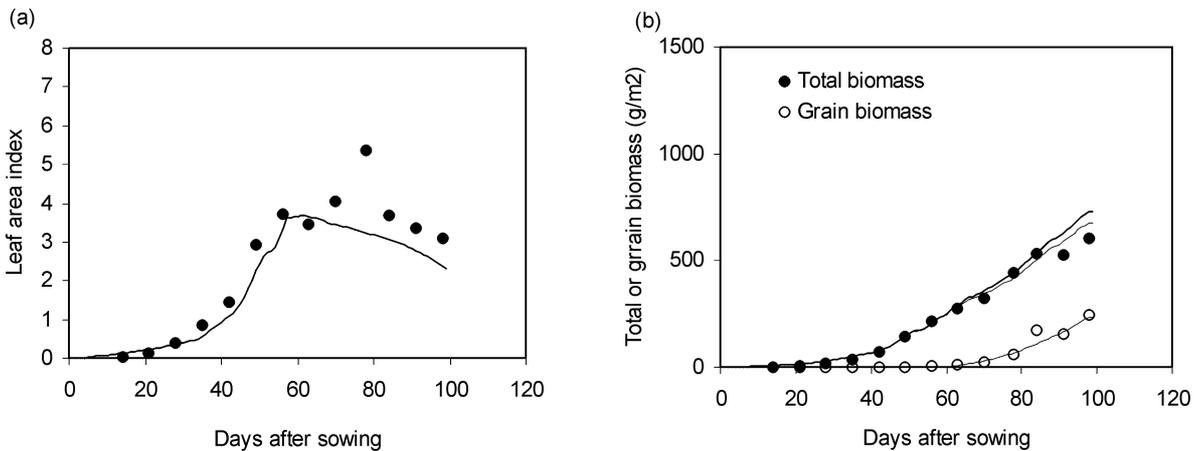


Fig. 3. Observed and simulated: (a) LAI, and (b) total and green biomass and grain biomass in an irrigated extra-short duration pigeonpea crop (cv. ICPL 84023) sown on 20 June 1994 on an alfisol at Patancheru at a plant density of 33 plants m⁻².

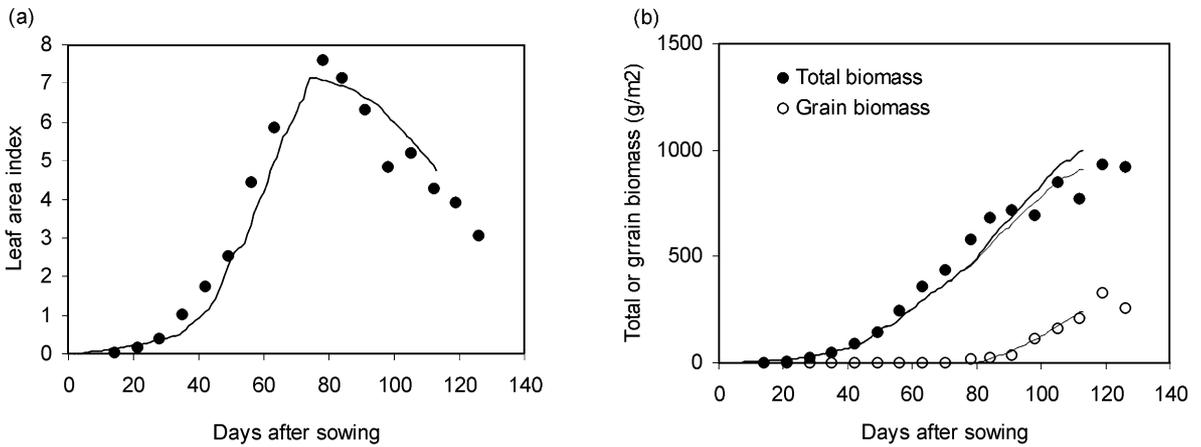


Fig. 4. Observed and simulated: (a) LAI, and (b) total and green biomass and grain biomass in an irrigated short-duration pigeonpea crop (cv. ICPL 87) sown on 20 June 1994 on an alfisol at Patancheru at a plant density of 33 plants m⁻².

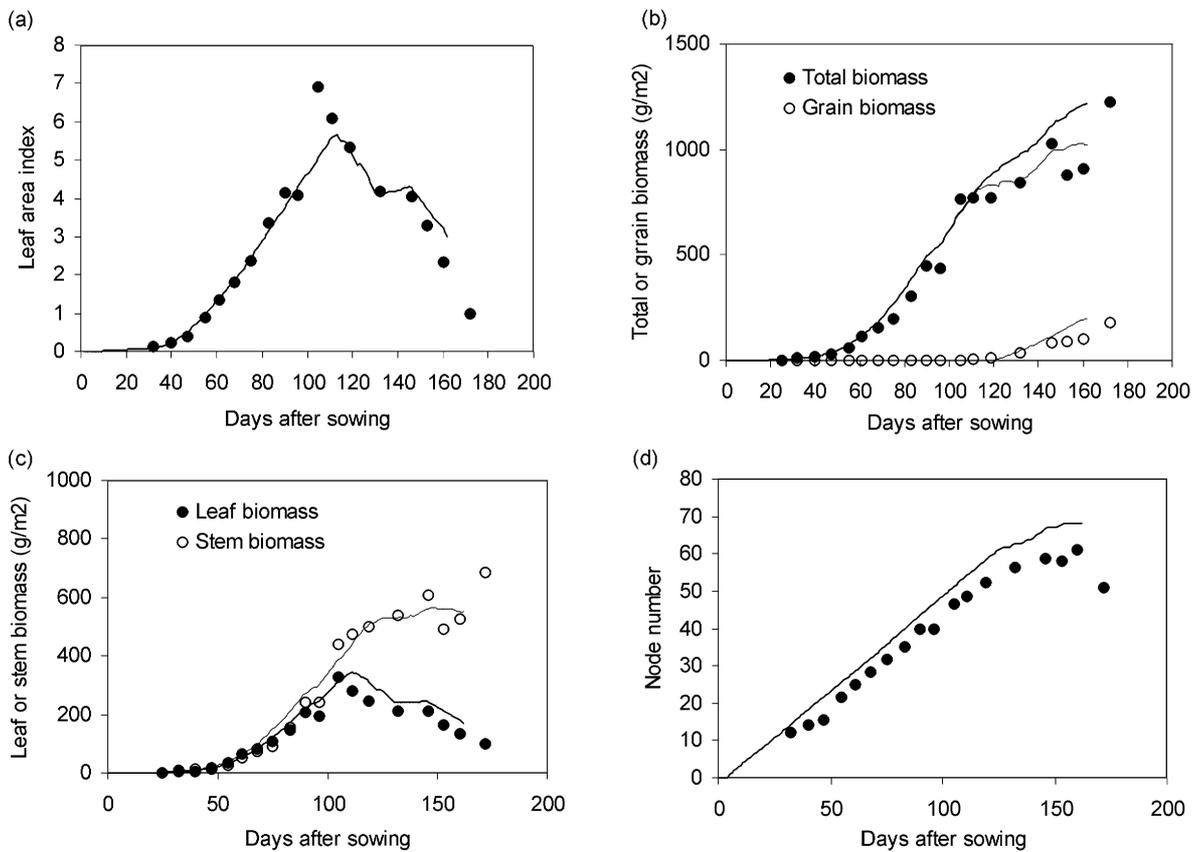


Fig. 5. Observed and simulated: (a) LAI, (b) total and green biomass and grain biomass, (c) green leaf and stem biomass, and (d) mainstem node number in an irrigated medium-duration pigeonpea crop (cv. C11) sown on 21 June 1991 on an alfisol at Patancheru at a plant density of 4.4 plants m⁻².

Figs. 3–5, respectively. All examples are of crops sown at ICRISAT in the wet season, on alfisol soils with irrigation applied to minimise water deficit. The model captures the pattern of LAI and the expected differences in peak LAI across the three main cultivar groups. The extent of leaf senescence and detachment in pigeonpea near maturity can be variable, therefore both the simulated total biomass (inclusive of senesced leaves) and green biomass (exclusive of senesced leaves) is plotted for comparison with observed values. The time course and final values of total biomass (ca. 700, 900 and 1200 g m⁻²) are well simulated for the three groups, and within the simulated total and green biomass values. Fig. 5 shows extra detail of growth and development detail for a medium-duration cultivar, cv. C11. It reveals that biomass is simulated well, as also is partitioning

between leaf and stem. Node number increases continuously until the end of grain fill in medium-duration cultivars, and this phenomenon is reproduced well by the model (Fig. 5d).

Water deficit is an important constraint to pigeonpea production, and Fig. 6 gives an example of the capability of the model to simulate water deficit effects for a crop (cv. C11) sown in the wet season without irrigation. Although, this is the wet season, water stress can occur if crop maturity extends beyond the end of the rains. In this example, the crop developed substantial mid-season water stress, as shown by the decrease in LAI before flowering at 70–100 das (Fig. 6a). The model is able to capture the effects of this period of water stress on the time-course of LAI, and biomass and components (Fig. 6a–c). There is no effect of water stress in the model on node appearance,

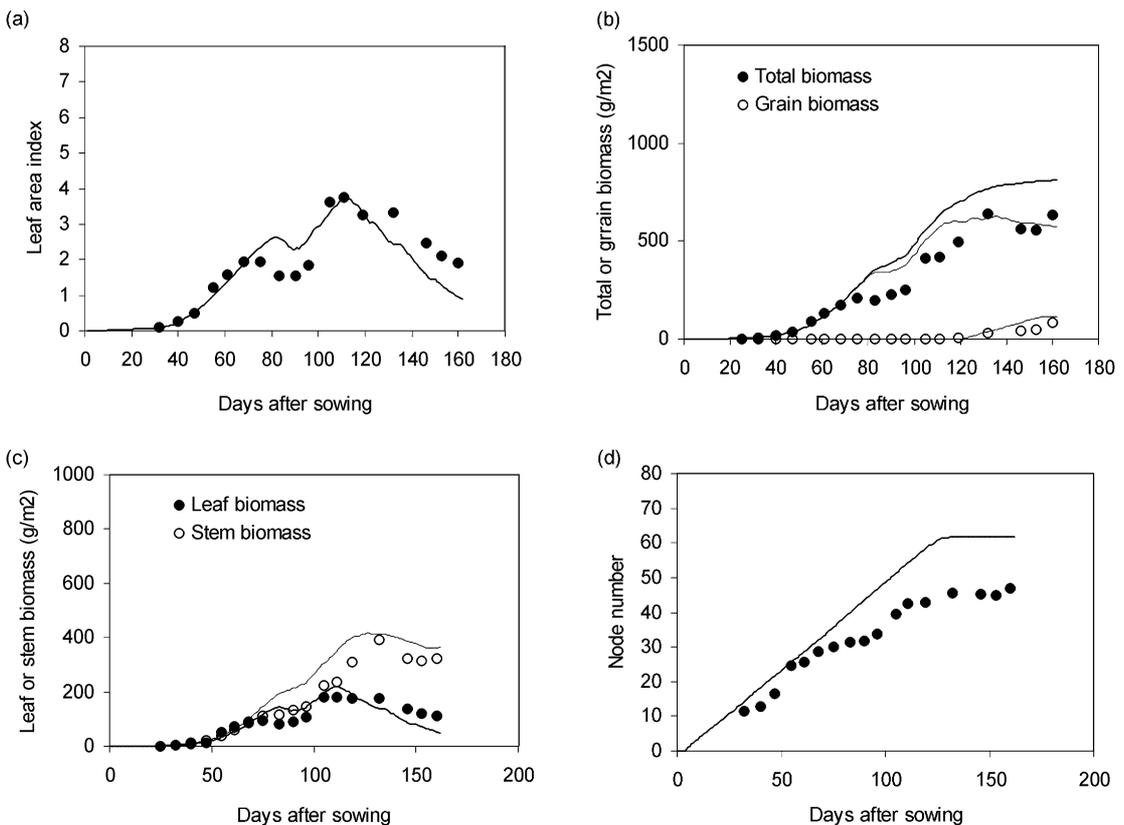


Fig. 6. Observed and simulated: (a) LAI, (b) total and green biomass and grain biomass, (c) green leaf and stem biomass, and (d) mainstem node number in a dryland medium-duration pigeonpea crop (cv. C11) sown on 21 June 1991 on an alfisol at Patancheru at a plant density of 4.4 plants m⁻².

Table 5

Root mean square of deviations (RMSD), mean, linear regression statistics (R^2 , slope and intercept) for observed vs. simulated values and number of observations used in comparing the model performance against observed data. Values in parentheses are calculated excluding data sets where waterlogging probably influenced crop productivity

	RMSD		Mean	Observed vs. simulated regression			N
	Absolute value	% of mean observed		R^2 (%)	Slope	Intercept	
Time to flowering (days)	4.3	5.6	77.2	96	0.92	6.6	24
Time to maturity (days)	9.8	7.8	126.6	92	0.85	14.6	24
Green biomass at maturity (kg ha ⁻¹)	2056 (2019)	29.2 (28.7)	7037 (6983)	74 (80)	0.64 (0.62)	2686 (2596)	34 (29)
Grain yield (kg ha ⁻¹)	332 (276)	18.2 (16.1)	1828 (1813)	76 (84)	0.84 (0.82)	385 (387)	34 (29)

hence the over prediction from 70 das onwards (Fig. 6d) as expected. Water deficit effects on canopy development in the model operate via the rate of area expansion, rather than through the rate of appearance of leaves.

Grain yield was simulated well by the model with an RMSD of 332 g m⁻², being 18.2% of the observed mean grain yield (Table 5). The R^2 value for observed vs. simulated regression was 76%. Green biomass at maturity was simulated less well — overall the model over predicted biomass as shown by the large positive intercept for the regression of observed vs. simulated. The difficulty in gaining good agreement between simulated and observed biomass at maturity is due, in part, to the issue of variable leaf loss in pigeonpea, referred to above.

It was possible to identify some of the reasons for poor agreement between simulated and observed biomass and yield in Fig. 7. In particular, waterlogging was thought to limit crop growth in some data sets — those that experienced heavy rain in the first half of the season and the observed data show a pause or a decrease in LAI in apparently well-watered conditions. The suspected waterlogging influence was more obvious on the vertisol, under irrigation, where waterlogging is often observed at ICRISAT (Chauhan, 1987). By way of example, Fig. 8a and b shows for a medium-duration crop grown at 33 plants m⁻² in the post-rainy season on a vertisol, that the model predicts growth and yield well under dryland conditions, whereas under irrigation (Fig. 8c and d), leaf area, growth and yield are all over-predicted. By

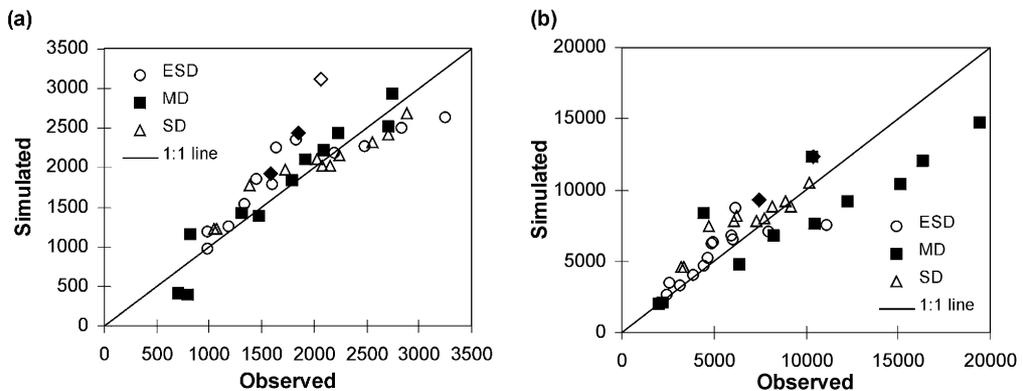


Fig. 7. Observed and simulated: (a) grain yield, (b) non-senesced (green) biomass at maturity. ESD: extra-short duration cultivars, SD: short-duration cultivars, M: medium-duration cultivars. The 1:1 line is shown. Data sets with suspected waterlogging limitation to growth are identified by the diamond symbol.

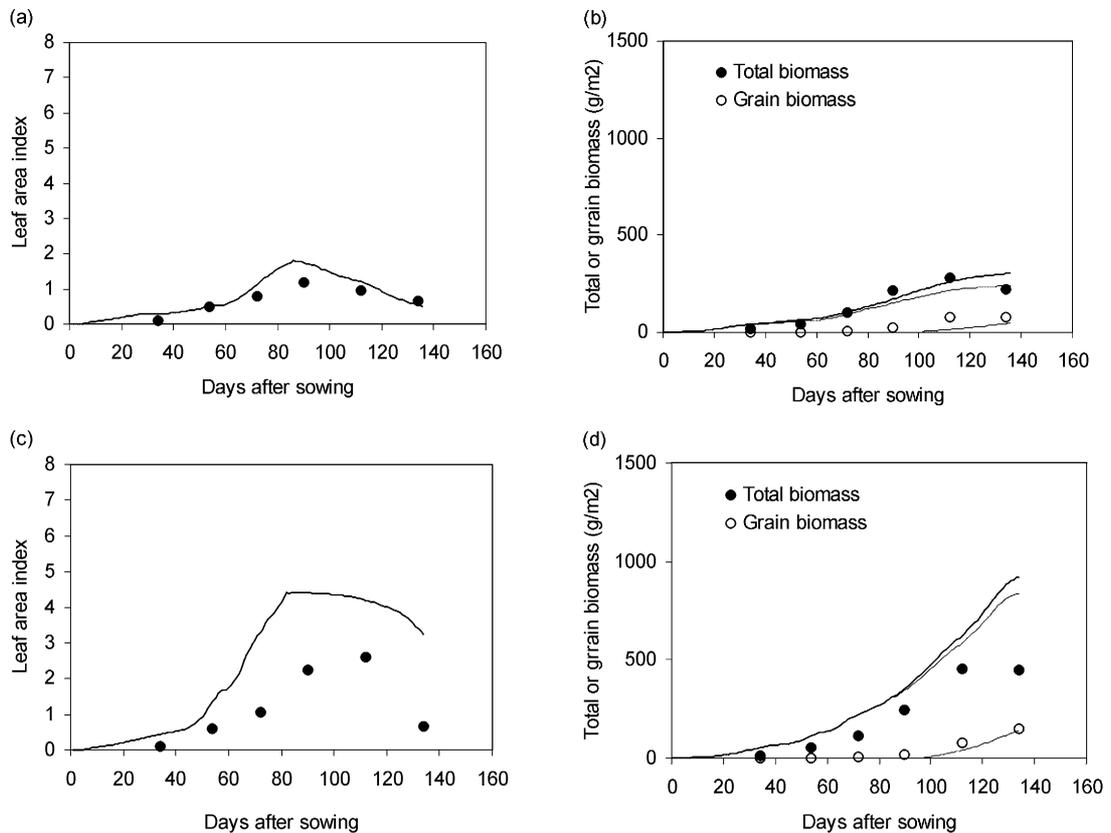


Fig. 8. Observed and simulated: (a) and (c) LAI, (b) and (d) total and green biomass and grain yield for a medium-duration cultivar cv. C11 sown on 16 October 1981 on a vertisol soil type at 33 plants m⁻², either under rainfed conditions ((a) and (b)) or under irrigation ((c) and (d)).

comparison, medium-duration crops grown at this density under irrigation in the wet season would reach LAI of 6 or more (e.g. Fig. 5), indicating some additional constraint operating in the case of the crop in Fig. 8. The capability to simulate waterlogging effects in pigeonpea awaits better definition of many functional relationships. Exclusion of five of the 38 data sets where waterlogging impacts was considered likely, improved the RMSD as a percentage of the observed mean grain yield from 18.2 to 16.1% and the R^2 for the observed vs. predicted regression for grain yield from 76 to 84% (Table 5).

The set of experiments used to test the model, while all conducted at Patancheru, India, encompassed a wide range in yield levels due to manipulation of the key agronomic variables of sowing date, density, cultivar, irrigation, and soil type. Hence, the model could be used with some confidence outside central

India. Carberry et al. (2001) showed that the phenology sub-model predicted flowering dates at locations in northern India and eastern Africa, and with some verification against local data there is no reason why it should not be able to predict growth and yield in these environments also.

4. Conclusions

This paper reports a crop simulation model for pigeonpea, a widely cultivated grain legume in the tropics. The model gives good predictive capability for pigeonpea phenology, leaf area, biomass and grain yield, despite the relatively simple approach taken. A key feature of this model is that relatively few parameters (phenology, partitioning during grain fill) are used to define each maturity type, yet satisfactory

predictions of phenology and yield are possible across a wide range of cultivars. We have identified further areas for model improvement including waterlogging effects on crop growth. A pressing need is to test the model in intercropping situations. If this is successful, the model should find increasing application in analyses of pigeonpea production.

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