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Simulating coconut growth, development and yield with the InfoCrop-coconut model

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Summary Simulation modeling of perennial crops has immense potential for generating information for plantation managers. We report the development of the InfoCrop-coconut model and its application to coconut (*Cocos nucifera* L.) growing in diverse tropical and subtropical environments. The model is based on the generic crop model InfoCrop that simulates various annual crops in tropical and subtropical regions. The InfoCrop-coconut model was calibrated and validated with data compiled from published studies comprising many physiological, agronomical and nutritional experiments conducted between 1978 and 2005 in diverse geographic locations throughout India. The treatments included various water and nutrient regimes and varieties of coconut. Time to first flowering varied between 4 and 6 years, leaf production varied from 8 to 15 leaves year^{-1} and nut yield ranged from 3000 to 27,000 nuts ha^{-1} year^{-1}. The genetic coefficients used for calibration and validation were generated from field experiments conducted during 1995–2005. Model efficiency and validation performance were analyzed statistically. Simulated trends in phenological development, total dry mass and its partitioning, and nut yield agreed closely with observed values, although a 15% error was observed in a few cases. Considering that field measurements have an experimental error of 10–15% and wide variation existed within treatments, the model adequately simulated the effects of management practices and agro-climatic conditions over short periods. For a range of agro-climatic zones, simulated potential yields varied from 26 to 30 Mg ha^{-1} year^{-1} and potential annual dry mass production varied from 52 to 62 Mg ha^{-1}, depending on environment. We conclude that InfoCrop-coconut can be used to increase the efficiency of agronomic experiments designed to aid coconut crop management.

Keywords: calibration, crop model, dry mass, phenology, potential yields, simulation, validation.

Introduction

Coconut (*Cocos nucifera* L.) is a perennial crop grown mainly in the tropics and subtropics of India, the Philippines, Malaysia, Sri Lanka, and Indian Ocean and South Pacific islands. Coconut is a multi-utility palm that plays a significant role in the economy of these countries, including 10 million farming communities in India. The annual demand for coconut-based products is projected to increase to about 17 billion nuts by 2020 (Naresh Kumar 2007). Hence, the importance of finding improved varieties and of optimizing irrigation and nutritional management.

Systematic experimentation on crop growth, development and yield in different agro-climatic environments through traditional methods and tools is expensive, time consuming and requires large experimental areas for a perennial crop like coconut. An alternative, less costly approach involves crop simulation models (Penning de Vries et al. 1989, Kropff et al. 1996).

Dynamic crop models simulate crop growth processes and their interactions with the soil and environment. Once calibrated and validated, a model can simulate the effects of various factors like management practices, soil factors and water availability on coconut growth, dry mass production, partitioning, nut yields and crop nitrogen uptake. Such models have been used for other crops, particularly annual crops, to characterize the effects of environmental variables and agro-ecological zoning (Nix 1987, Aggarwal 1993), to define research priorities and technology transfer (Jones and O'Toole 1987, Kropff et al. 1996), to estimate production potential (Aggarwal 1988), for strategic and tactical decision making (Angus et al. 1993) and to predict the effects of climate change and climatic variability (Adams et al. 1990, Aggarwal and Sinha 1993). Godin and Caraglio (1998) have used multi-scale models to simulate plant topological structures.

Simulation models of plantation crops are scarce, and none exist for coconut. Parsimonious models for coconut yield predictions are based solely on weather parameters for one (Vijayakumar et al. 1988, Peiris and Thatttil 1998) or several locations (Naresh Kumar et al., unpublished results). These models have limited adaptability to a wide range of climatic, soil and agronomic conditions. Recently, Zuidema et al. (2003) described a simulation model for perennial crops like cocoa. Modeling of perennial tree growth and tree architecture was reported by Reffye et al. (1997). AMAPmod software based on 3D mock-ups of apple plant architecture has also been developed (Godin et al. 1999). However, a comprehensive model that simulates coconut growth, development and yield under varying conditions is unavailable. We attempted to develop, calibrate and validate a simulation model for the entire 60-year economic life span of coconut.

Our objectives were to: (1) describe the development, calibration and validation of the InfoCrop-coconut model for coconut; and (2) use this model to quantify potential yields in different agro-climatic zones of India. A generic crop model InfoCrop, developed in India for simulating growth and yield of annual crops in the tropics and subtropics (Aggarwal et al. 2004), was adapted for coconut.

Materials and methods

Model description

The InfoCrop-coconut model is written in FORTRAN SIMULATION TRANSLATOR (FST) language (Van Kraalingen 1995). The time step of the model is one day. The general structure and details of the InfoCrop series of models are described by Aggarwal et al. (2004). Here, we present the key features of the adaptation of the model for coconut.

Phenological development The InfoCrop-coconut model simulates the complete life cycle of coconut in three developmental phases: (1) seed nut planting to emergence; (2) juvenile period (emergence to first flowering); and (3) nut yield phase, throughout the 60-year economic life of a coconut tree. Seed nuts take 70 (in dwarf varieties) to 90 days (in tall varieties) to germinate. Tall varieties take 6 to 7 years for first flowering, whereas dwarf varieties take around 4 years, and hybrids about 5 years. One inflorescence emerges in the axil of each leaf at about monthly intervals. Thus, from a single coconut palm, nuts of different maturity can be obtained at any given time. Nuts mature about 12 months after pollination. The period between first flowering and the stable nut yield stage is defined as the unstable yield phase. Generally, nut yield production stabilizes about 14 years after planting, and tall varieties continue to yield for about 60 years, whereas dwarf varieties and hybrids yield for about 45 years (Menon and Pandalai 1960, Rajagopal et al. 2005). Daily rate of phenological development in each of these four stages is a function of thermal time, which is modified by day and night temperatures, and the availability of nitrogen and water.

The critical photoperiod is 12 h, above which flowering in coconut is hastened. Flowering can be initiated 2 months earlier by maintaining the trees in continuous light (Pillai et al. 1973). Therefore, the emergence and juvenile periods are considered photosensitive in the model. However, under natural conditions, trees face both long days and short days in any given year. The effect of temperature is more prominent than the effect of day length in determining phenological events in the post-juvenile phase of coconut. The growing degree day (GDD) requirement for successive leaf and spathe opening is about 415 GDD (Naresh Kumar unpublished data). Flowering is influenced by C–N metabolism and by the accumulation of insoluble and soluble carbohydrates. Insoluble carbohydrates accumulate when daily sunshine duration is around 8–9 h with no rainfall, and soluble carbohydrates accumulate when daily sunshine duration is around 2–3 h with adequate rainfall (Kasturi Bai and Ramadasan 1983). The soluble carbohydrate fraction enhances leaf production, whereas inflorescence development and production are strongly associated with the initiation of the inflorescence (Patel 1938). Leaf and inflorescence initiation are affected by low temperatures. A well distributed annual rainfall of 130–230 cm, with a mean annual temperature of 27 ± 5 °C, radiation of 250–350 W m^{-2} and sunshine for 120 h month^{-1} provide optimum conditions for coconut growth and yield (Child 1974). The optimum minimum and maximum temperatures are 20 and 35 °C, respectively. Low temperatures with short days delay leaf and inflorescence emergence. Prolonged temperatures of less than 10 °C for 1 month trigger nut fall. Temperatures above 40 °C, which prevail during April–July in the tropics, result in low vapor pressure deficits leading to increased leaf mortality thus reducing the functional leaf area index (LAI). These temperature effects are accounted for in the model by decreasing the rate of development if nighttime temperatures fall below 10 °C or if daytime temperatures exceed 40 °C.

Dry mass production After seedling emergence, crop growth is calculated as a function of radiation-use efficiency (RUE) and radiation interception. An RUE of 1.2 to 1.4 g MJ^{-1} of solar irradiance is reported for coconut (Corley 1983, Foale 1993, Jayasekara et al. 1996). In the model, an RUE of 2.4 g MJ^{-1} is used, assuming that photosynthetically active radiation is 50% of incident solar irradiance (Gardner et al. 1988). Crop development stage, temperature, atmospheric CO_2 concentration and the availability of nitrogen and water all influence RUE.

Dry mass partitioning among plant organs Potential dry mass (DM) production in coconut is estimated to be about 51 Mg ha^{-1} year^{-1} (Corley 1983). Annual DM partitioning to stem (2–6%), leaf (18–33%), inflorescence (4–6%) and nut (61–70%) varies with cultivar, management practice and agro-climatic zone (Rajagopal et al. 1989, Kasturi Bai et al. 1996, 1997, Kasturi Bai and George 2002, Siju Thomas 2003, Naresh Kumar 2007). Dry mass partitioning to root, stem, leaf and nut as a function of development stage is simulated in the model through empirical interpolation functions developed from field experiments. The root:shoot ratio is affected by nitrogen and water availability and is simulated in the model by empirical interpolation functions. Dry mass is accumulated over time in the stem. Leaf DM is divided into two components: that of leaves on the tree and that of dead leaves. The model can generate the cumulative DM of a tree of any age. Inflorescence DM, excluding nut DM, is summed on a cumulative basis with stem DM. Nut DM is formed every day, and a part is harvested every month. In the model, cumulative nut DM is simulated on a daily basis and summed monthly.

Leaf growth and senescence The LAI is calculated by multiplying leaf mass by a crop-age-dependent specific leaf area. Specific leaf area (SLA) of coconut seedlings has been reported to be 160 $cm^2 g^{-1}$ (Kasturi Bai and Ramadasan 1990). The SLA decreases with tree age, and in adult palms, the SLA is only about 70 $cm^2 g^{-1}$ (Kasturi Bai and George 2002). Leaf senescence is simulated through the effects of leaf shading, development stage, temperature, and nitrogen and water availability. Increasing LAI above 4 through continued growth of leaves hastens the death of shaded leaves. The source–sink relationship is influenced by soil water availability (Naresh Kumar et al. 2006)

Crop senescence takes place earlier at high temperatures, and low temperatures accelerate leaf death. Water and nitrogen limitations hasten leaf senescence.

Root growth Coconut has an adventitious root system, and rooting depth in the model is limited by maximum rooting depth and soil depth. The mean maximum rooting depth of coconut is generally about 100 cm with only a few roots reaching a depth of 200 cm (Menon and Pandalai 1960). Rooting depth is also dependent on growth rate, which is modified by crop development stage, soil impedance, and nitrogen and water availability.

Floral biology Tall forms of coconut flower about 6 years after planting and dwarf forms flower about 4–5 years after planting (Menon and Pandalai 1960). The time from inflorescence initiation to nut maturity is normally 44 months (Rajagopal et al. 1996), and any stress during panicle initiation, ovary development, and button and fist size nut phase, decreases nut yield (Rajagopal et al. 1996). Factors influencing pistillate flower production and button shedding include varietal variations, irrigation, nutrition, leaf area and DM production (Kasturi Bai et al. 2003, Naresh Kumar et al. 2006).

Soil water and nitrogen balance The InfoCrop-coconut model simulates water and nitrogen balance in three soil layers. The model simulates infiltration of water from rainfall and irrigation to the surface soil layer, evaporation, transpiration, drainage and water fluxes. If rainfall exceeds the infiltration rate and storage capacity of soil, runoff occurs. Above field capacity, any additional water entering the soil surface percolates beyond the lower boundary of the rooting zone. Waterlogging may occur if the rate of precipitation or irrigation exceeds the hydraulic conductivity of any soil layer. Depending on the variety and developmental stage, soil waterlogging affects crop growth and water uptake. Water stress is estimated as the difference between available soil water and evapotranspiration, which is calculated by the modified Penman Monteith formula (FAO 56).

Nitrogen within a soil layer is assumed to be uniformly distributed. The model simulates various soil processes such as urea hydrolysis, nitrification, denitrification, immobilization, volatilization, biological N_2 fixation, nitrogen movement and crop uptake (Aggarwal et al. 2004). Soil nitrogen balance is the sum of NH_4-N and NO_3-N in each soil layer. Soil nitrogen stress is estimated as the difference between available nitrogen and losses through crop uptake, volatilization and leaching.

Nut yield The InfoCrop-coconut model calculates all allocations to different plant parts as DM. Nut DM is converted to partially dry nut by multiplying by a variety-specific nut fresh:dry mass ratio. Nut DM is partitioned into copra, which is the solid endosperm in coconut fruit (23–30%), shell, which is the endocarp of the coconut fruit (21–31%), and husk, which is the mesocarp (40–56%) (Siju Thomas 2003, Naresh Kumar 2005). The harvest index (HI) for copra varies from 16 to 20%, and for nut DM, HI varies from 51 to 64% based on above-ground annual DM production (Kasturi Bai and George 2002). In the model, the number of nuts is simulated but the mass of individual nuts is not.

Model input requirements Model inputs include soil, plant, daily weather and crop management data. (1) For three soil layers: depth (mm), organic carbon (%), soil texture (% sand, silt and clay), bulk density, field capacity, permanent wilting point, and NH_4-N and NO_3-N content are required. (2) Plant: among the phenological parameters required are thermal time for germination, juvenile phase and economic yielding phase. Among the crop growth parameters, seed rate, relative growth rate of leaf area, RUE, specific leaf area of variety, dry nut mass, fraction of copra and oil in nut are required. (3) Daily weather: data needed for the model are minimum and maximum air temperatures (°C), solar radiation (kJ m^{-2} day^{-1}), vapor pressure (kPa), wind speed (m s^{-1}) and rainfall (mm). (4) Crop management: amount and dates of fertilizers applied, fertilizer application method (sub-soil or surface application) and irrigation details such as amount, frequency and method (drip irrigation or flood irrigation).

Output and verifiable variables The standard output of InfoCrop-coconut comprises development time and stage, daily crop growth, DM of roots, stem and leaves, total DM and cumulative values of leaf mass, stem mass, nut yield and nut number. In addition, LAI, crop nitrogen uptake, soil water and nitrogen availability, evapotranspiration, and nitrogen and water stress are obtained as output. Amounts of irrigation and fertilizer applied are also included in the outputs.

Calibration

The model was calibrated with data from field experiments for a few tall and dwarf coconut varieties grown under well-fertilized and irrigated conditions between 1945 and 2005 at the Central Plantation Crop Research Institute (CPCRI), in the Kasaragod district (12°18′ N, 75° E) of India. Generally, growth and morphological characters of palms vary significantly between tall and dwarf forms. Tall varieties have almost similar stem, leaf and growth characters but differ significantly in nut characteristics. Dwarf varieties have shorter and more slender stems and less canopy area than tall varieties, and nuts of various shapes, sizes and colors. To simulate a crop variety, the model requires genetic coefficients related to phenology, GDDs required for germination, the vegetative phase and nut development, relative growth rate of leaf area, specific leaf area, RUE, etc. Detailed physiological experiments in the field and in controlled environments are needed to directly estimate these values.

Because no single published experiment provided all of the required calibration data, a three-pronged approach was adopted. (1) Data on photosynthetic characteristics, leaf area, DM production and partitioning to leaf, stem, inflorescence and nuts, nut yield and nut composition parameters were taken from a varietal experiment, consisting of seven cultivars, conducted at CPCRI, Kasaragod. Data were collected over 5 years. Data from earlier experiments at CPCRI, Kasaragod and from the literature (Ratnambal et al. 1995) were used to determine coefficients for DM partitioning, leaf area characteristics, and nut characteristics. Variety-specific nut composition coefficients were obtained from published studies (Kasturi Bai and George 2002, Naresh Kumar 2005). (2) Parameters related to thermal time for different phenological stages and the relationship of photosynthesis to weather parameters were taken from experiments conducted in different agro-climatic zones (Rajagopal et al. 2000, Rajagopal and Naresh Kumar 2002). (3) Unpublished data from the CPCRI, Kasaragod (Naresh Kumar unpublished data) and published data were used to derive photosynthetic response curves to temperature, solar irradiance and atmospheric CO_2 concentration (Jayasekara et al. 1996, 2000, Rajagopal et al. 2000, Gomes et al. 2002*a*, 2002*b*, 2006, Naresh Kumar and Kasturi Bai, unpublished results). Optimal weather conditions for growth and yield were obtained from Child (1974). Some of the coefficients, like RUE, of different varieties were estimated by repeated iterations until a close match between simulated and measured growth and yield was obtained. Although large variation in RUE among cultivars is not known, the model provides RUE as a variety-specific parameter for future input management. Dwarf coconut varieties have a lower RUE (around 2.0) than tall varieties. Phenology was matched for each variety based on such factors as thermal time required for germination and flowering. These coefficients were used in the subsequent validation and application. Of the 10 experiments used for validation, only one was used for calibration.

Model validation

The calibrated model was used to simulate experiments conducted over multiple years at different locations. These areas represent various agro-climatic zones; namely, hot sub humid to per humid western coastal plains (Kasaragod, Kerala and Ratnagiri, Maharastra) and hot semiarid inlands (Arisikeri, Karnataka and Aliyarnagar, Tamil Nadu) (Table 1a), and they represent the states responsible for about 85% of coconut production in India.

Many experiments have been conducted in India to study the effects of different agro-ecological factors, such as variety, nitrogen, irrigation and weather, on growth and yield of coconut plantations. Among these experiments, several were selected that reported values for the inputs required for our model validation. The experimental details used for model validation are given in Table 1b. This dataset included experiments from the west coast, east coast and interior Karnataka and Tamil Nadu areas conducted between 1976 and 2005. For the selected set of experiments, maximum temperatures varied from 14 to 47.5 °C, and minimum temperatures varied from 4.4 to 35.0 °C across locations and seasons. Annual rainfall varied from 688 to 3500 mm.

Experiments consisted of several treatments. Each treatment differed in location or variety or in nitrogen or water management (Table 1b). The database consisted of popular varieties and hybrids. Weather data for these locations was collected from their respective research stations. Representative soil profiles were taken from the literature (Sankaranarayanan and Velayutham 1976*a*, 1976*b*, Khan et al. 1978, Cecil and Khan 1993, Naidu et al. 1997). Soils at these locations varied from littoral sandy to sandy loam to red and black loam soils to red laterite soils in texture. Organic carbon varied from 0.6 to 1.4%, depending on the region and experiment. The effects of the nitrogen fertilizer and irrigation regimes measured in the different studies were used in the simulation.

Evaluation of model performance

Four statistical measures and indices were applied to evaluate the model that included mean bias error (MBE) (Addiscott and Whitmore 1987); root mean square error (RMSE) (Fox 1981), index agreement (IA) (Willmott 1982) and modeling efficiency (ME) (Nash and Sutcliffe 1970):

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i) \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{2}$$

$$\mathrm{IA} = \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}\left(|S_i - \bar{O}| + |O_i - \bar{O}|\right)^2} \tag{3}$$

Table 1a. Characteristics of study locations at the Central Plantation Crop Research Institute, in the Kasaragod district of India (AICRP 2000–2006).

Study site	Latitude (N)	Longitude (E)	Elevation (m)	Temperature (°C)		Annual rainfall (mm)
				Maximum	Minimum	
Kasaragod	12°18′	75°	10.7	23.0–38.4	15–29	3497
Arisikeri	12°48′	78°	510	14.0–38.5	4.4–25	688
Aliyarnagar	10°17′	77°30′	279	19.5–40.0	11.4–29.5	779
Ratnagiri	17°	73°24′	3	17.8–42.5	11.5–35	3035

Table 1b. Details of experiments at each site included for validation and application of the InfoCrop-coconut model.

Experiment	Duration	Treatments	Soil type	Annual yield (10^3 nuts ha^{-1})	Source
Kasaragod					
Cultivars and hybrids	1994–2005	7	Red sandy loam	7.0–19.4	Kasturi Bai and George 2002
Drip irrigation	1992–1999	5	Red laterite; sandy	10.0–20.3	Naresh Kumar et al. 2002; Dhanapal et al. 2003, 2004*a*, 2004*b*
NPK	1988–2000	27	Littoral sandy	3.2–14.7	Srinivasa Reddy et al. 2002
HDMSC[1]	2001	3	Red sandy loam	22.0–27.5	Maheswarappa et al. 2004
Soil water conservation	1998–2004	9	Different agroclimatic zones	8.4–27.0	Naresh Kumar et al. 2006
Arisikeri					
Drip irrigation	2000–2005	5	Red sandy loam	8.9–23.5	AICRP 2000–2006
NPK	2000–2005	27	Black clayey loam	5.6–13.3	AICRP 2000–2006
Aliyarnagar					
Drip irrigation	2000–2005	5	Red sandy loam	12.8–28.4	AICRP 2000–2006
Ratnagiri					
Drip irrigation	1997–2005	5	Sandy loam	7.4–19.8	AICRP 2000–2006
NPK	2000–2005	27	Sandy loam	13.7–21.2	AICRP 2000–2006

[1] HDMSC = high density multi-species cropping system.

$$ME = \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \qquad (4)$$

where n is the number of samples, S_i and O_i are the simulated and observed values, respectively, and $\overline{O}$ is the mean of the observed data. The MBE indicates bias of model error as it accounts for positive and negative deviations. The RMSE describes mean absolute deviation between simulated and observed values. Accuracy of simulation is characterized by lower RMSE. The IA, which ranges between 0 and 1, is another method for evaluating modeling performance. Similar to the coefficient of determination, the closer IA is to 1, the better the simulation. Another parameter, ME, in contrast to IA, allows negative values and compares deviation between simulated and observed state variables with the variance of observed values. The r^2 of conventional statistics was calculated to estimate linearity between measured and simulated values of development, growth and yield.

Results and discussion

Validation

Phenological development The InfoCrop-coconut model simulates the coconut life cycle in three developmental stages: planting to emergence; emergence to first flowering; and flowering phase until maturity. Daily rate of phenological development in each developmental stage is a function of thermal time, which is modified by photoperiod, day/night temperatures and the nitrogen and water stress experienced by the crop.

Published data on the effects of day length on germination and flowering in coconut are scarce. A 24-h day length hastened flowering (Pillai et al. 1973), whereas nitrogen and water stress delayed flowering in coconut by several months. The critical mean day temperature is 23 °C, above which germination and flowering can be adversely affected. The optimum temperature is 15–22 °C, and the maximum is 25–34 °C. A minimum temperature above 10 °C is important to trigger flowering. In areas where minimum temperatures are lower than 10 °C during winter, flowering is delayed and only 7–8 inflorescence emerge per year versus 12–13 under optimal conditions. Optimal irrigation and nitrogen supply increase inflorescence production by two inflorescences per year. Minimum temperatures below 15 °C for several nights trigger shedding of fertilized flowers, which is called "button shedding." These effects have been considered in the model by decreasing the rate of development if night temperatures fall below 15 °C. Very high temperatures during April–August also cause button shedding, decreasing nut yield, even though inflorescence production is not influenced.

The entire phase from emergence to the economic growth period is considered photo- and thermo-sensitive in the model. Long photoperiods and optimal temperatures favor early flowering. The critical photoperiod is 12 h, above which flowering is hastened. Rate of development is high in long photoperiods and low in short photoperiods. The model delays flowering and hastens maturity under conditions of nitrogen and water limitation.

Under field conditions, tall cultivars take about 90 days for germination, whereas dwarf cultivars take about 70 days for germination (Menon and Pandalai 1960). Initial flowering occurs around the 6th year in coconut, and dwarf coconut flower earlier. These simulations were made by incorporating the thermal time required for each of the phases, and the simulations matched field observations. Economic yields are obtained from coconut trees for about 60 years, and simulations can be made on a daily basis for up to 60 years provided weather data are available. Nitrogen or water stress hastened the termination of coconut economic productivity and tree mortality. These phenological simulations corroborated experimental data obtained under field conditions.

Leaf area and dry mass partitioning In coconut plantations, LAI attains a maximum value at the stabilized yield stage at around 14 years after planting and maintains this value until the economic crop yield phase (Menon and Pandalai 1960). In the model, LAI increased from the seedling stage through the juvenile phase. Stabilized LAI coincides with stabilized nut yield, probably reflecting a stabilized source–sink balance. In adult palms, stabilization of LAI occurs when the death rate of leaf area is compensated by growth in leaf area. However, this trade off is influenced by factors such as nitrogen and water availability and weather conditions, as occur under field conditions. The measured maximum leaf area index (LAI_{max}) in treatments varying in weather, location, nitrogen and water management and cultivar ranged from 2.5 to 4. Simulated LAI_{max} was linearly correlated ($r^2 = 0.81$) with measured values. The RMSE for LAI_{max} was 6% of the mean of measured values (Table 2).

Measured mean annual DM production in 15-year-old plantations varied from about 8000 to 13,500 kg ha^{-1} depending on agro-climatic conditions and cultivar (Table 3). These values increased when simulated for trees in the stabilized yield phase under rain-fed and full-management conditions. Simulated total dry mass (DM_{tot}) was linearly correlated ($r^2 = 0.83$ at Arisikeri to 0.95 at Kasaragod) with measured values. The RMSE for DM_{tot} was 4.76% of the mean of measured values (Table 2). Similarly, measured and simulated values for DM_{leaf}, DM_{stem} and DM_{nut} were highly correlated (Table 4). In the model, DM of inflorescence (excluding nut DM) is combined with stem DM (DM_{stem}). The overall correlation coefficient between simulated and measured values for DM_{tot} and DM of different plant parts was 0.96 (Figure 1), indicating a high simulation accuracy across locations, treatments and cultivars.

Nut yield Nut yield is greatly influenced by nitrogen and water availability. Measured nut yield in the datasets varied from 18 to 162 nuts tree^{-1} year^{-1} depending on location, cultivar, nitrogen supply and water availability. Measured and simulated nut yields showed good agreement ($r^2 = 0.86$) (Figure 2), and estimated errors were acceptable (Table 2). The RMSE was 11% of the mean of measured values. Similarly, measured nut dry yield showed a strong linear relationship ($r^2 = 0.81$ at Arisikeri to 0.94 at Kasaragod) with simulated nut dry yield (Table 4). The RMSE for nut dry yield was 9.16% of the mean of measured values (Table 2). Simulated nut yields were within 15% of measured values. Measured and simulated nut yields were highly correlated at Kasaragod ($r^2 = 0.97$) followed by Ratnagiri ($r^2 = 0.87$), Aliyarnagar and Arisikere ($r^2 = 0.84$) (Figure 3). Similarly, measured and simulated nut yields in different soil types were significantly correlated (Figure 4), indicating sensitivity of the model to soil type. Nuts are harvested almost once a month in coconut gardens. In the model, yield is

Table 2. Statistical indicators of InfoCrop-coconut model performance. Abbreviations: LAI_{max}, maximum leaf area index; DM_{leaf}, leaf dry mass; DM_{stem}, dry mass of stems and inflorescences; DM_{tot}, total dry mass; DM_{nut}, nut dry mass; MBE, mean bias error; RMSE, root mean square error; IA, index of agreement; ME, model efficiency; and r^2, linear regression coefficient.

Indicator	Simulated output							
	Germination	Yield commencement	LAI_{max}	DM_{leaf}	DM_{stem}	DM_{tot}	DM_{nut} yield	Nut yield
MBE	−5.29	−0.07	0.44	−143	−171	163	−23	3.18
RMSE	9.41	2.49	0.26	516	245	543	967	12.52
IA	0.93	0.96	0.74	0.87	0.71	0.99	0.96	0.96
ME	0.73	0.87	−0.78	0.71	0.02	0.98	0.91	0.85
r^2	0.87	0.88	0.81	0.81	0.63	0.98	0.96	0.86

Table 3. Comparison of experimental measurements and InfoCrop-coconut simulated values of annual dry mass production (kg ha^{-1} year^{-1}) and partitioning in coconut plantations with different soil types. Abbreviations: DM_{leaf}, leaf dry mass; DM_{stem}, dry mass of stems and inflorescences; DM_{nut}, nut dry mass; DM_{tot}, total dry mass; Meas., measured; and Sim., simulated.

Soil type	Varieties	DM_{leaf} production		DM_{stem} production		DM_{nut} production		DM_{tot} production	
		Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
Kasaragod									
Littoral sandy	9	4641	5337	1663	2009	7513	7450	13,318	14,796
Arisikeri									
Black clayey loam	8	3885	4244	1360	1629	4288	5441	8050	11,314
Aliyarnagar									
Red sandy loam	12	3850	5140	1540	2003	8680	7202	12,845	14,345

Table 4. Regression coefficients of measured versus InfoCrop-coconut simulated values for leaf area index (LAI), nut yield, dry masses of nut (DM_{nut}), leaf (DM_{leaf}) and stem plus inflorescence (DM_{stem}), and total dry mass (DM_{tot}).

Site	LAI	Nut yield	DM_{nut}	DM_{leaf}	DM_{stem}	DM_{tot}
Kasaragod	0.84	0.97	0.94	0.89	0.88	0.95
Arisikeri	0.81	0.85	0.81	0.81	0.71	0.83
Aliarnagar	0.80	0.85	0.87	0.81	0.73	0.9
Ratnagiri	0.83	0.87	0.83	0.89	0.76	0.91

cumulated on a daily basis. Monthly or annual yields can be calculated by subtracting the previous value from the targeted value.

Cumulating DM and nut yield over the entire period of simulation allows estimation of net primary production and carbon flow in the system. Thus, the model can be easily updated to calculate carbon sequestration potentials and carbon stocks in coconut plantations.

Model efficiency

Model efficiency ranged from 0.73 to 0.98 for LAI, nut yield commencement, DM partitioning and nut yield against an optimum ME of 1.0 showing high model efficiency (Table 2). Corresponding values of RMSE ranged from 4.8 to 11.0% of the mean of measured values indicating only a small error of estimation. The MBE ranged from −171 to 163, indicating slight under- and overestimation. Values of r^2 ranged from 0.63 to 0.98 showing close linear agreement between measured and simulated values (Table 2). The IA varied from 0.71 to 0.99, indicating a high degree of agreement between simulated and measured values. The maximum for this parameter is 1. Thus, the InfoCrop-coconut model simulated crop growth, development and yield of coconut in subtropical environments of the Indian peninsular region within acceptable limits of error based on a validation dataset comprising widely contrasting treatments that included locations, soils, seasons, weather, varieties, crop management, and water and nitrogen regimes.

Potential total dry mass and yields in different agro-climatic zones

Coconut growth and productivity are greatly influenced by environmental and management factors. Potential coconut DM_{tot} production is reported to be as high as 51 Mg ha^{-1} year^{-1} based on physiological calculations (Corley 1983, Foale 1993), compared with the realized maximum of 32 Mg ha^{-1} year^{-1} in irrigated and well-managed plantations and about 20 Mg ha^{-1} year^{-1} in rain-fed plantations (Kasturi Bai et al. 1996, 1997, Naresh Kumar et al., unpublished results). Corley (1983) reported a value of 30 Mg ha^{-1} year^{-1} for a 'Dwarf' × 'West African Tall' hybrid growing in the Ivory Coast. To assess the environmental suitability of coconut in different agro-climatic zones, potential DM_{tot} production and potential yields were simulated. The model simulates potential DM_{tot} production and potential yields based on solar irradiance and RUE as a function of weather parameters, with all other factors being non-limiting. Simulated potential DM_{tot} production varied across the agro-climatic zones, from around 52 Mg ha^{-1} year^{-1} in central southern plateau and hill zone of Karnataka, to 62 Mg ha^{-1} year^{-1} in the southern plateau and hills zone of Tamil Nadu (Table 5). These two locations are interior sun-ex-

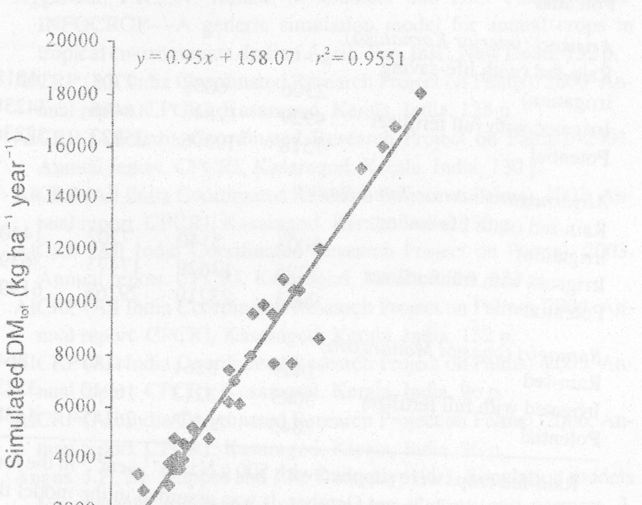

Figure 1. Measured versus InfoCrop-coconut simulated total dry mass (DM_{tot}) production and partitioning in coconut cultivars grown under different agro-climatic zones and management conditions.

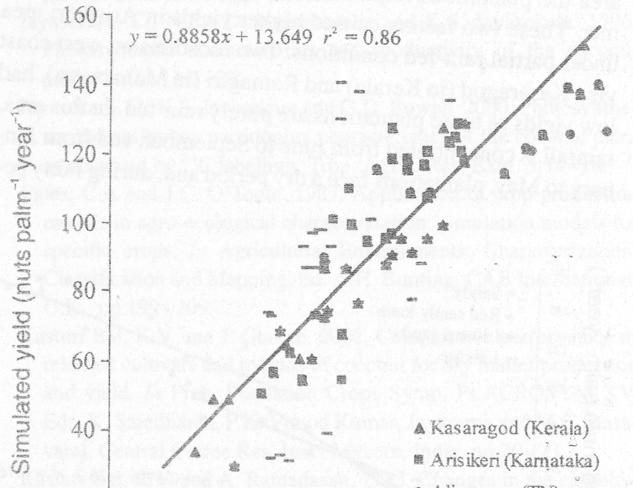

Figure 2. Measured versus InfoCrop-coconut simulated nut yield in coconut cultivars grown under different agro-climatic zones and management conditions.

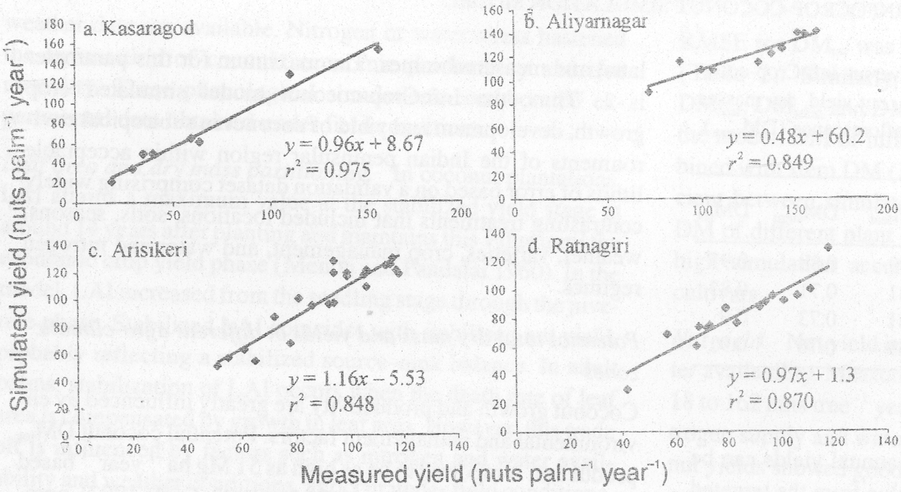

Figure 3. Agro-climatic zone-wise validation of the InfoCrop-coconut simulation model in terms of measured versus simulated nut yield in coconut cultivars grown under different management conditions.

posed lands. However, temperatures in parts of Karnataka (Arisikeri area) are high during April to June and low during December and January thus lowering potential DM production. On the other hand in the Tamil Nadu areas, temperatures are more conducive for longer growth periods. In areas located on the west coast of India, potential DM production is 55 Mg ha^{-1} year^{-1}. These areas have adequate sunlight for most of the year except during the rainy season with suitable and stable temperatures. Potential yields varied from 25 to 30 Mg ha^{-1} year^{-1} depending on the agro-climatic zone (Table 5). Results indicate higher productivity potential in eastern Tamil Nadu. In this location the yield of well-managed plantations is higher than in any other coconut growing location considered in this study. (Table 5, Figure 3) (AICRP 2000–2006). Nut yields in parts of Karnataka are higher because rainfall distribution is better, even though it is a low rainfall zone. However, in this area the plantations require lifesaving irrigation during summer. These two factors caused higher yields in Arisikeri area under partial rain-fed conditions. Two locations on west coast viz., Kasaragod (in Kerala) and Ratnagiri (in Maharastra), had low yields as these plantations are purely rain-fed. In this area, rainfall is concentrated from June to September, and from January to May, plantations face a dry period and, during rainy periods, reduced sunshine, both of which affect potential DM_{tot} and potential yield. Estimates of potential yields indicate that improved agronomic management will result in higher yields

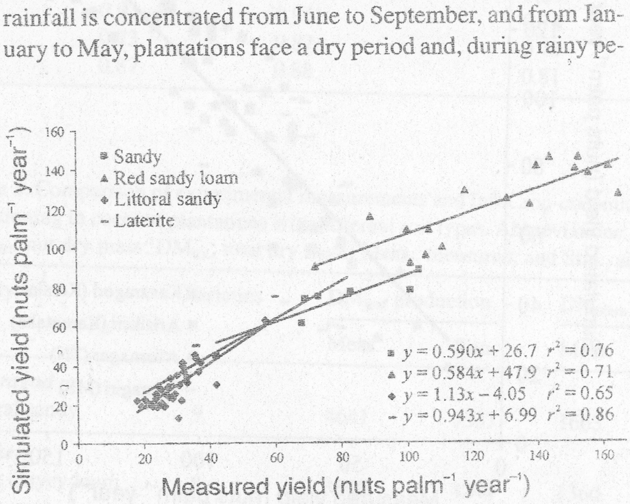

Figure 4. Measured versus InfoCrop-coconut simulated nut yield in coconut cultivars grown in different soil types.

Table 5. InfoCrop-coconut simulated values for dry mass production (kg ha^{-1} year^{-1}) and its partitioning in coconut under rain-fed and well-managed (irrigated and well fertilized) and most intensive management (potential) of palms in stabilized yield phase in different agro-climatic zones in India. Abbreviations: DM_{stem}, dry mass of stem and inflorescence; DM_{leaf}, leaf dry mass; DM_{nut}, nut dry mass; and DM_{tot}, total dry mass.

Treatment	DM_{stem}	DM_{leaf}	DM_{nut}	DM_{tot}
Kasaragod (north Kerala)				
Rain-fed[1]	1166	3019	3871	8056
Irrigated with full fertilizer[2]	4715	12215	15660	32588
Potential	8042	20865	26750	55658
Arisikeri (interior Karnataka)				
Rain-fed (with life-saving irrigation)	2306	6008	7703	16018
Irrigated with full fertilizer	4929	12843	16466	34238
Potential	7518	19596	25122	52236
Aliyarnagar (interior Tamil Nadu)				
Rain-fed (with life-saving irrigation)	2003	5140	7202	14400
Irrigated with full fertilizer	5295	13629	17473	36398
Potential	9013	23219	29768	61998
Ratnagiri (coastal Maharastra)				
Rain-fed	1449	3261	4180	8648
Irrigated with full fertilizer	5083	13213	16940	35237
Potential	7845	20393	26145	54383

[1] Rain-fed crops were supplied with 500 g N tree^{-1} year^{-1} in the form of urea during July and October. It was assumed in the model that the P_2O_5 and K_2O were non-limiting.

[2] Irrigated + fertilized crops were irrigated at 200 l tree^{-1} every 4 days during non rainy periods and fertilized with 1000 g N tree^{-1} year^{-1} in the form of urea applied in two split doses during July and October in 2:3 and 1:3 ratios, respectively. It was assumed in the model that phosphorus and potassium were non-limiting.

in coconut plantations in India, particularly in Tamil Nadu.

We conclude that the model satisfactorily simulates coconut DM production, partitioning and nut yield. It is also useful for assessing potential yields of coconut in different agro-climatic zones. The model can simulate multi-location trials providing an alternative to genetic and agronomic experiments and thereby reducing the need for long-term studies. Model simulations can be employed as a tool for management, agro-ecological zoning and coconut yield forecasting. The model will be made available to interested research and management groups.

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References

Adams, R.M., C. Rosenzwig, R.M. Peart et al. 1990. Global climate change and US agriculture. Nature 345:219–224.

Addiscott, T.M. and A.P. Whitmore. 1987. Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. J. Agric. Sci. 109:141–157.

Aggarwal, P.K. 1988. Wheat production in south-east Asia—Potential and constraints. Outlook Agric. 17:49–53.

Aggarwal, P.K. 1993. Agro-ecological zoning using crop simulation models: characterization of wheat environments of India. *In* Systems Approach to Agricultural Development. Eds. F.W.T. Penning de Vries and P.S. Teng. Kluwer Academic Publishers, Dordrecht, pp 97–109.

Aggarwal, P.K. and S.K. Sinha. 1993. Effect of probable increase in carbon dioxide and temperature on productivity of wheat in India. J. Agric. Meteorol. 48:811–814.

Aggarwal, P.K., N. Kalara, S. Chander and H.C. Pathak. 2004. INFOCROP—A generic simulation model for annual crops in tropical environments. Indian Agric. Res. Inst., New Delhi, 132 p.

AICRP (All India Coordinated Research Project on Palms). 2000. Annual report. CPCRI, Kasaragod, Kerala, India, 135 p.

AICRP (All India Coordinated Research Project on Palms). 2001. Annual report. CPCRI, Kasaragod, Kerala, India, 130 p.

AICRP (All India Coordinated Research Project on Palms). 2002. Annual report. CPCRI, Kasaragod, Kerala, India, 133 p.

AICRP (All India Coordinated Research Project on Palms). 2003. Annual report. CPCRI, Kasaragod, Kerala, India, 133 p.

AICRP (All India Coordinated Research Project on Palms). 2004. Annual report. CPCRI, Kasaragod, Kerala, India, 132 p.

AICRP (All India Coordinated Research Project on Palms). 2005. Annual report. CPCRI, Kasaragod, Kerala, India, 96 p.

AICRP (All India Coordinated Research Project on Palms). 2006. Annual report. CPCRI, Kasaragod, Kerala, India, 96 p.

Angus, J.F., M. Stapper and J.R. Donnelly. 1993. Simulation models for strategic and tactical management of crops and pastures. J. Agric. Meteorol. 48:775–778.

Cecil, S.R. and H.H. Khan. 1993. Nutritional requirement of coconut and coconut based farming systems in India. *In* Advances in Coconut Research and Development. Eds. M.K. Nair, H.H. Khan, P. Gopalasundaram and E.V.V. Bhaskara Rao. Oxford & IBH, New Delhi, pp 257–275.

Child, R. 1974. Coconuts, 2nd Edn. S. Longman, London, 335 p.

Corley, R.H.V. 1983. Potential productivity of tropical perennial crops. Exp. Agric. 19:217–237.

Dhanapal, R., H.P. Maheswarappa, P. Subramanian and A.K. Upadhyay. 2003. Influence of drip irrigation on growth, nut characters and yield of coconut in littoral sandy soil. Coconut Res. Dev. 18:1–23.

Dhanapal, R., H.P. Maheswarappa and P. Subramanian. 2004*a*. Influence of drip irrigation on growth, nut characters and yield of coconut (*Cocos nucifera*) on laterite soil. Coconut Res. Dev. 19:32–38.

Dhanapal, R., H.P. Maheswarappa, C.V. Sairam, P. Subramanian and A.K. Upadhyay. 2004*b*. Influence of drip irrigation on growth and yield of coconut (*Cocos nucifera*) on laterite soil. J. Plant. Crops 32:26–30.

Foale, M.A. 1993. Physiological basis for yield in coconut. *In* Advances in Coconut Research and Development. Eds. M.K. Nair, H.H. Khan, P. Gopalasundaram and E.V.V. Bhaskara Rao. Oxford & IBH, New Delhi, pp 181–189.

Fox, D.G. 1981. Judging air quality model performance: a summary of the AMS Workshop on dispersion model performance. Bull. Am. Meteorol. Soc. 62:599–609.

Gardner, F.P., R.B. Pearce and R.L. Mitchell. 1988. Physiology of crop plants. Iowa State University Press, Ames, pp 3–30.

Godin, C. and Y. Caraglio. 1998. A multiscale model of plant topological structures. J. Theor. Biol. 191:1–46.

Godin, C., Y. Guedon and E. Costes. 1999. Exploration of a plant architecture database with the AMAPmod software illustrated on an apple tree hybrid family. Agronomie 19:163–184.

Gomes, F.P., M.S. Mielke and A.A.F Almeida. 2002*a*. Leaf gas exchange of green dwarf coconut (*Cocos nucifera* L. var. *nana*) in two contrasting environments of the Brazilian north-east region. J. Hortic. Sci. Biotechnol. 77:766–772.

Gomes, F.P., M.S. Mielke, A.A.F. Almeida and W.S. Muniz. 2002*b*. Leaf gas exchange in two dwarf coconut genotypes in the south-east of Bahia state, Brazil. Coconut Res. Dev. 28:37–55.

Gomes, F.P., M.A. Olivam, M.S. Mielke, A.A.F. Almeida and H.G. Leite. 2006. Photosynthetic irradiance-response in leaves of dwarf coconut palm (*Cocos nucifera* L. '*nana*', Arecaceae): comparison of three models. Sci. Hortic. 109:101–105.

Jayasekara, C., N.P.A.D. Nainanayake and K.S. Jayasekara. 1996. Photosynthetic characteristics and productivity of the coconut palm. Cocos 11:7–20.

Jayasekara, C., K.S. Jayasekara and G.D. Bowen. 2000. Photosynthesis and assimilate partitioning characteristics of the coconut palm as observed by ^{14}C labelling. Trop. Agric. Res. Extn. 3:14–18.

Jones, C.A and J.C. O'Toole. 1987. Application of crop production models in agro-ecological characterization: simulation models for specific crops. *In* Agricultural Environments: Characterization, Classification and Mapping. Ed. A.H. Bunting. CAB International, U.K., pp 199–209.

Kasturi Bai, K.V. and J. George. 2002. Comparative performance of released cultivars and hybrids of coconut for dry matter production and yield. *In* Proc. Plantation Crops Symp. PLACROSYM XV. Eds. K. Sreedharan, P.K. Vimod Kumar, Jayarama and M.C. Basavaraj. Central Coffee Res. Inst., Mysore, India, pp 20–23.

Kasturi Bai, K.V. and A. Ramadasan. 1983. Changes in the carbohydrate fractions as a function of environmental variables in hybrids and tall coconut palms. *In* Coconut Research and Development. Ed. N.M. Nayar. Wiley Eastern, pp 203–209.

Kasturi Bai, K.V. and A. Ramadasan. 1990. Growth studies in coconut seedlings. J. Plant. Crops 18:130–133.

Kasturi Bai, K.V., V. Rajagopal, C.D. Prabha, M.J. Ratnambal and M.V. George. 1996. Evaluation of coconut cultivars and hybrids for dry matter production. J. Plant. Crops 24:23–28.

Kasturi Bai, K.V., V. Rajagopal, D. Balasimha and P. Gopalasundaram. 1997. Water relation, gas exchange and dry matter production of coconut (*Cocos nucifera* L.) under unirrigated and irrigated conditions. Coconut Res. Dev. 13:45–58.

Kasturi Bai, K.V., D.V. Sreenivasa Reddy, M.J. Ratnambal and R.H. Laxman. 2003. Factors contributing to female flower production and button shedding in coconut. J. Plant. Crops 31:33–36.

Khan, H.H., M.P. Sankaranarayanan and K.B. Narayana. 1978. Characteristics of coconut soils of India. I. Morphology, some physio-chemical characteristics and taxonomy. *In* Proc. Plantation Crops Symp. I. Ed. E.V. Nelliat. Indian Soc. Plantation Crops, Kasaragod, Kerala, India, pp 54–79.

Kropff, M.J., P.S. Teng, P.K. Aggarwal, B. Bouman, J. Bouma and H.H. van Laar. 1996. Applications of systems approaches at the field level. Vol. 2. Kluwer Academic Publishers, Dordrecht, 456 p.

Maheswarappa, H.P., M.R. Hegde, R. Dhanapal, C.V. Sairam and T.V. Singh. 2004. Impact of integrated mixed farming systems in coconut (*Cocos nucifera*) garden on coconut yield and economic analysis. Ind. J. Agron. 46:56–63.

Menon, K.P.V. and K.M. Pandalai. 1960. The coconut palm: a monograph. Times of India Press, Bombay, 350 p.

Naidu, L.G.K., P. Krishnan, K.M. Nair and K.R. Venugopal. 1997. Evaluation of land suitability of major coconut (*Cocos nucifera* L.) growing areas in India. Ind. J. Agric. Sci. 67:58–62.

Naresh Kumar, S. 2005. Variability in content and composition of fatty acids in coconut oil due to genetic and environmental factors. AP Cess Fund Project Final Report, ICAR, New Delhi, 103 p.

Naresh Kumar, S. 2007. Climate change effects on growth and productivity of plantation crops with special reference to coconut and black pepper: impact, adaptation and vulnerability and mitigation strategies. ICAR Network Project Final Report, ICAR, New Delhi, 21 p.

Naresh Kumar, S., V. Rajagopal, R.H. Laxman, R. Dhanapal and H.P. Maheswarappa. 2002. Photosynthetic characteristics and water relations in coconut palms under drip irrigation levels. *In* Plantation Crops Research and Development in the New Millennium. Proc. PLACROSYM XIV. Eds. P. Rathinam, H.H. Khan, V.M. Reddy, P.K. Mandal and K. Suresh. Coconut Development Board, Kochi, pp 116–120.

Naresh Kumar, S., V. Rajagopal, S.T. Thomas and V.K. Cherian. 2006. Effect of conserved soil moisture on the source–sink relationship in coconut (*Cocos nucifera* L.) under different agro-climatic conditions in India. Ind. J. Agric. Sci. 76:277–281.

Nash, J.E. and I.V. Sutcliffe. 1970. River flow forecasting through conceptual-model. J. Hydrol. 273:282–290.

Nix, H. 1987. The role of crop modeling, minimum data sets and geographical information systems in the transfer of agricultural technology. *In* Agricultural Environments: Characterization, Classification and Mapping. Ed. A.H. Bunting. CAB International, U.K., pp 113–117.

Patel, J.S. 1938. The coconut. A monograph. Govt. Press, Madras, India, 102 p.

Peiris, T.S.G. and R.O. Thattil. 1998. The study of climate effects on the nut yield of coconut using parsimonious models. Exp. Agric. 34:189–206.

Penning de Vries, F.W.T., D.M. Jansen, H.M.F. ten Berge and A. Bakema. 1989. Simulation of ecophysiological processes of growth in several annual crops. Simulation monographs 29. Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, The Netherlands, 271 p.

Pillai, R.V., R.B. Nair, C. Mathew, K.V.A. Bhavappa and A. Ramadasan. 1973. Studies on photoperiodic responsive reaction in coconut. J. Plant. Crops 1:89–92.

Rajagopal, V. and S. Naresh Kumar. 2002. Characterization of drought in different coconut growing areas and drought management strategies. Indian Council of Agricultural Res., New Delhi, 84 p.

Rajagopal, V., A. Ramadasan, K.V. Kasturi Bai and D. Balasimha. 1989. Influence of irrigation on leaf water relations and dry matter production in coconut palms. Irrig. Sci. 10:73–81.

Rajagopal, V., S. Shivashankar and J. Mathew 1996. Impact of dry spells on ontogeny of coconut fruits and its relation to yield. Plantat. Res. Dev. 3:251–255.

Rajagopal, V., S. Naresh Kumar, K.V. Kasturi Bai and R.H. Laxman. 2000. Day time fluctuations in photosynthetic parameters and water relations in juvenile palms of coconut grown under rainfed and irrigated conditions. J. Plant Biol. 27:27–32.

Rajagopal, V., V.A. Parthasarathy, S. Naresh Kumar, D.V.S. Reddy and R. Iyer. 2005. Coconut. *In* Plantation Crops. Vol 2. Eds. V.A. Parthasathy, P.K. Chattopadhyay and T.K. Bose. Naya Udyog Pub., Kolkata, pp 1–178.

Ratnambal, M.J., M.K. Nair, K. Muraleedharan, P.M. Kumaran, E.V.V. Bhaskara Rao and R.V. Pillai. 1995. Coconut descriptors part I. CPCRI, Kasaragod, 197 p.

Reffye, Ph. De, T. Fourcaud, F. Blasie, D. Barthelemy and F. Houllier. 1997. A functional model of tree growth and tree architecture. Silva Fenn. 31:297–311.

Sankaranarayanan, M.P. and M. Velayutham. 1976*a*. Coconut soils on east coast of India. Coconut Bull. Oct/Nov, pp 13–14.

Sankaranarayanan, M.P. and M. Velayutham. 1976*b*. Soils that support coconut in west coast. Indian Farm. 27:21–23.

Siju Thomas, T. 2003. Photosynthetic characteristics, dry matter production and nut yield in coconut (*Cocos nucifera* L.) cultivars in two different agro-climatic regions. Ph.D. Thesis, Mangalore University, India, 203 p.

Srinivasa Reddy, D.V., A.K. Upadhyay, P. Gopalasundaram and H. Hameed Khan. 2002. Response of high yielding coconut variety and hybrids to fertilization under rainfed and irrigated conditions. Nutr. Cycling Agroecosys. 62:131–138.

Van Kraalingen, D.W.G. 1995. The FSE system for crop simulation: version 2.1. Quantitative approaches in system analysis report 1. C.T. de Wit Grad. Sch. Production Ecol. AB-DLO. Wageningen, The Netherlands, 58 p.

Vijayakumar, K., P.T.N. Namiar, C.H. Jacob Mathew, C.H. Amarnath and T.K. Balakrishnan. 1988. Forecasting of yield in coconut by using weather variables. J. Plant. Crops (Suppl.) 16:463–468.

Willmott, C.J. 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 64:1309–1313.

Zuidema, P.A., W. Gerritsma, L. Mommer and P.A. Leffelaar. 2003. A physiological production model for cocoa: model description and technical programme manual of CASE2 version 2.2. Wageningen University, The Netherlands, 145 p.