A simulation model of cereal–legume intercropping systems for semi-arid regions

I. Model development

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Abstract

Cereal–legume intercropping plays an important role in subsistence food production in developing countries, especially in situations of limited water resources. Crop simulation can be used to assess risk for intercrop productivity over time and space. In this study, a simple model for intercropping was developed for cereal and legume growth and yield, under semi-arid conditions. The model is based on radiation interception and use, and incorporates a water stress factor. Total dry matter and yield are functions of photosynthetically active radiation (PAR), the fraction of radiation intercepted and radiation use efficiency (RUE). One of two PAR sub-models was used to estimate PAR from solar radiation; either PAR is 50% of solar radiation or the ratio of PAR to solar radiation (PAR/SR) is a function of the clearness index ($K_T$). The fraction of radiation intercepted was calculated either based on Beer’s Law with crop extinction coefficients ($K$) from field experiments or from previous reports. RUE was calculated as a function of available soil water to a depth of 900 mm (ASW). Either the soil water balance method or the decay curve approach was used to determine ASW. Thus, two alternatives for each of three factors, i.e., PAR/SR, $K$ and ASW, were considered, giving eight possible models (2 methods × 3 factors). The model calibration and validation were carried out with maize–bean intercropping systems using data collected in a semi-arid region (Bloemfontein, Free State, South Africa) during seven growing seasons (1996/1997–2002/2003). The combination of PAR estimated from the clearness index, a crop extinction coefficient from the field experiment and the decay curve model gave the most reasonable and acceptable result. The intercrop model developed in this study is simple, so this modelling approach can be employed to develop other cereal–legume intercrop models for semi-arid regions.

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Keywords: Available soil water; Crop model; Intercropping; Radiation interception; Radiation use efficiency

1. Introduction

Intercropping has long been practiced by small-scale farmers in the tropics. In particular, cereal and legume intercropping is recognised as a common
cropping system in developing tropical countries (Ofori and Stern, 1987). Typically, C₄ cereal crops such as maize (Zea mays L.), pearl millet [Pennisetum glaucum (L.) R.Br.] and sorghum [Sorghum bicolor (L.) Moench] are the dominant plant species, whereas C₃ legume crops such as beans (Phaseolus vulgaris L.), cowpea [Vigna unguiculata (L.) Walp.], groundnut (Arachis hypogaea L.), pigeonpea [Cajanus cajan (L.) Millsp.] and soybean [Glycine max (L.) Merr.] are the associated or secondary species. Canopy structures and rooting systems of cereal crops are generally different from those of legume crops. In most cereal–legume intercropping, cereal crops form higher canopy structures than legume crops, and the roots of cereal crops grow to a greater depth than those of legume crops. This suggests that the component crops probably have differing spatial and temporal use of environmental resources. Intercrops may make use of environmental resources such as radiation, water and nutrients more efficiently than monocrops (Willey, 1990).

Crop productivity mainly depends on the amount of radiation intercepted by crops when other factors, such as water, nutrients, disease and weeds, are not limiting (Loomis and Williams, 1963). Many studies have shown a positive correlation of crop production to the amount of radiant energy intercepted by the crop (Monteith, 1977; Tsubo et al., 2001). Compared with sole cropping, intercropping has greater radiation capture potential and utilisation because of the effect of combination of differing spatio-temporal use of radiation among component crops (Willey, 1990). Many crop models have been developed for monoculture production systems (Jones et al., 2003; Keating et al., 2003; Van Ittersum et al., 2003). However, few satisfactory crop models simulate polyculture (Probert et al., 1998; Baumann et al., 2002; Berntsen et al., 2004). The objective of this study was to develop a semi-empirical model for cereal–legume intercrop growth and grain production under semi-arid conditions. In southern Africa, small-scale farmers usually grow beans as an intercrop with maize as a staple crop (Snapp et al., 1998). The model developed at University of the Free State, South Africa was calibrated and validated using intercropping and sole cropping systems of maize and beans under rainfed and irrigated conditions in a semi-arid environment.

2. Data collection

Field experiments were carried out at two sites (Agrometeorology site: 29°06′S, 26°11′E, 1411 m; Soil Science site: 29°01′S, 26°09′E, 1354 m; 15 km apart) of the Department of Soil, Crop and Climate Sciences, University of the Free State, South Africa during seven summer-crop growing seasons (1996/1997–2002/2003). The soil of both sites belongs to aridic ustorthents according to the USDA Soil Taxonomy system of classification; however, the soil at the Agrometeorology site had higher clay content than the Soil Science site. The agronomic information and treatments are summarised in Table 1. The experiments were carried out under both rainfed and irrigation conditions, with ample fertilizer application. The treatments comprised three planting dates (November, December and January), two row orientations, plant densities of 2.1–6.7 plants m⁻² for maize and 4.0–13.3 plants m⁻² for beans, and an inter-row spacing of 0.75–1 m for maize and 0.40–1.00 m for beans. The crop-row arrangement of intercropping systems for maize and beans were: (i) 0.75-m maize rows alternatively intercropped with a double bean row for the 1996/1997 and 1997/1998 seasons (row unit: maize–bean–bean–maize); (ii) 1.00-m maize rows intercropped with a single bean row for the 1998/1999 and 1999/2000 seasons (maize–bean); and (iii) 1.00-m maize rows intercropped with a double bean row for the 2000/2001, 2001/2002 and 2002/2003 seasons (maize–bean–bean). All the crops were planted by hand, and hand weeding was carried out during each growing season. The treatments were arranged in three or four randomised complete blocks. As the model was one-dimensional, it was necessary to cover a range of canopy architecture. Therefore, the model was developed using data from 1998/1999 and 2000/2001 and the first planting in 2001/2002, while its validation was conducted with data from 1996/1997, 1997/1998, 1999/2000, 2001/2002 (second planting) and 2002/2003 growing seasons (Mukhala, 1998; Tsubo, 2000; Ogindo, 2003).

Above-ground dry matter, leaf area and plant height were measured throughout the growing seasons. PAR (0.4–0.7 μm in wavelength; μmol s⁻¹) was measured above and beneath the crop canopies using...
Table 1  
Agronomic information and experimental treatments of the field experiments

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Crop variety</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>SNK2147 (medium/long duration)</td>
<td>SNK2147 (medium/long duration)</td>
<td>PAN6804 (short duration)</td>
</tr>
<tr>
<td>Beans</td>
<td>PAN127 (determinate)</td>
<td>PAN127 (determinate)</td>
<td>PAN148 (indeterminate)</td>
</tr>
<tr>
<td>Growing period</td>
<td>17–20 weeks</td>
<td>20 weeks</td>
<td>17 weeks</td>
</tr>
<tr>
<td>Sowing date</td>
<td>Early December</td>
<td>Late November</td>
<td>Late November, Mid January</td>
</tr>
<tr>
<td>Row orientation</td>
<td>North–South</td>
<td>North–South, East–West</td>
<td>East–West</td>
</tr>
<tr>
<td>Plant density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sole maize</td>
<td>–</td>
<td>6.7 plants m(^{-2})</td>
<td>4 plants m(^{-2})</td>
</tr>
<tr>
<td>Intercrop</td>
<td></td>
<td>13.3 plants m(^{-2})</td>
<td>8–10 plants m(^{-2})</td>
</tr>
<tr>
<td>Maize</td>
<td>2.2, 4.4, 6.7 plants m(^{-2})</td>
<td>6.7 plants m(^{-2})</td>
<td>4 plants m(^{-2})</td>
</tr>
<tr>
<td>Beans</td>
<td>2.1, 4.2, 6.3 plants m(^{-2})</td>
<td>6.7 plants m(^{-2})</td>
<td>8–10 plants m(^{-2})</td>
</tr>
<tr>
<td>Row spacing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sole maize</td>
<td>–</td>
<td>1.00 m</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Intercrop</td>
<td></td>
<td>0.50 m</td>
<td>0.40 m</td>
</tr>
<tr>
<td>Maize</td>
<td>0.75 m</td>
<td>1.00 m</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Beans</td>
<td>0.40 m(^{-1})1.10 m(^{-1})</td>
<td>1.00 m</td>
<td>0.40 m(^{-1})0.60 m(^{-1})</td>
</tr>
<tr>
<td>Plot size</td>
<td>6 m × 9 m</td>
<td>10 m × 15 m (98/99)</td>
<td>6 m × 6 m (99/00)</td>
</tr>
<tr>
<td>Size of final harvest area</td>
<td>12–23 m(^{2})</td>
<td>6–15 m(^{2})</td>
<td>12–16 m(^{2})</td>
</tr>
<tr>
<td>Rainfall + irrigation</td>
<td>813 mm (96/98) 815 mm (97/98)</td>
<td>636 mm (98/99) 723 mm (99/00)</td>
<td>250–350 mm</td>
</tr>
<tr>
<td>Basal fertilizer</td>
<td>254N, 67P, 33K (kg ha(^{-1}))</td>
<td>172N, 47P, 32K (kg ha(^{-1}))</td>
<td>240N, 96P, 48K (kg ha(^{-1}))</td>
</tr>
</tbody>
</table>

\( \text{a}\) Inter-row spacing of the double row beans intercropped between maize rows.

\( \text{b}\) Spacing between the double row beans.
3. Model description

3.1. A radiation-based crop model

As summarised by Sinclair and Gardner (1998), potential crop growth and yield result from four processes. First, the radiation interception by crop canopies provides the energy for crop production. Second, the efficiency of conversion of the intercepted radiation to plant mass determines the amount of dry matter produced. Third, the time required for plant radiation to plant mass determines the amount of dry (g MJ$^{-1}$ day of flowering). RUE for a vegetative stage is given by the following relationship:

$$TDM_i = TDM_k + \sum_{i=k+1}^{n} Y_i$$

where $Y$ is harvestable yield (g m$^{-2}$), and $n$ is the day of maturity. Therefore, if RUE is defined for the reproductive stage as the ratio of $Y$ to intercepted PAR, $Y$ (i.e., maize ears and bean pods) is given by:

$$Y_i = \sum_{i=k+1}^{n} (RUE_i \times F_i \times PAR_i)$$

Grain yield (i.e., maize kernels and bean seeds) is estimated from $Y$ using the ratio of grain dry mass to $Y$. In this study, the ratio measured during the 1998/1999 growing season was used (0.69 for maize and 0.72 for beans) (Tsubo, 2000).

3.1.2. Phasic development

Phasic development, time to emergence, flowering and maturity, can be determined by thermal time (degree days (DD): °C d). Emergence time is strongly dependent on soil water availability and temperature, and can be attained when thermal time reaches a specific DD and when cumulative rainfall after sowing reaches 25 mm. DD is calculated as follows:

$$DD_j = \sum_{j=1}^{m} (T_{\text{mean},j} - T_{\text{base},j})$$

where $j$ is days after planting (DAP), $m$ is the day of emergence (day $i = 1$), $T_{\text{mean}}$ is daily mean temperature, which is determined from daily maximum and minimum temperatures ($T_{\text{max}}$ and $T_{\text{min}}$, respectively), and $T_{\text{base}}$ is the base temperature (the lowest temperature at which growth and development stop). $T_{\text{mean}}$ is set to $T_{\text{base}}$ if less than $T_{\text{base}}$. $T_{\text{mean}}$ is set to the upper threshold temperature (the highest temperature at which growth and development are very slow, $T_{\text{upper}}$) if greater than $T_{\text{upper}}$. Flowering and maturity time ($k$-th and $n$-th days) are determined in the same manner. In general, $T_{\text{base}}$ varies from 0 to 3 °C for temperate crops and from 8° to 13 °C for tropical crops (Ong and Baker, 1985). For both cereal and legume crops, $T_{\text{base}}$ and $T_{\text{upper}}$ are set to 10 and 30 °C, respectively (Wallace and Enriqueze, 1980; McMaster and Wilhelm, 1997).
DD, as reported by Angus et al. (1981), can be used to determine emergence dates. DD to emergence after planting is 60.8, 39.5 and 47.9 °C d for maize, millet and sorghum, respectively, whereas it is 52.1 °C d for beans, 43.0 °C d for cowpea, 76.3 °C d for groundnut, 58.2 °C d for pigeonpea and 70.5 °C d for soybean. The average DD is 49.4 °C d for C4 cereal crops and 60.0 °C d for C3 legume crops. In this study, the DD for both C4 cereals and C3 legumes is assumed to be the same (i.e., average DD = 55 °C d). Using the monthly T\text{max} and T\text{min} data (30 years from 1961 to 1990 at Bloemfontein Airport, South Africa: 29°06'S, 26°18'E, 1351 m) and the length of each growth stage given by Allen et al. (1998) (initial, crop development, mid-season and late-season growth stages), average DD for vegetative and reproductive growth periods can be determined. The beginning of the mid-season stage is assumed to be flowering time, whereas the end of the late-season stage is maturity time. Planting dates of 1 November, 15 November and 1 December were used to determine DD for long, medium and short duration maize cultivars, respectively. For beans, the planting date of 1 December was employed. Table 2 summarises DD from emergence to flowering time and DD from flowering to maturity time, for both maize and beans.

3.2. Sub-models of the radiation-based crop model

3.2.1. Photosynthetically active radiation

Energy of PAR above the atmosphere is about 40% of radiation emitted by the sun. As solar radiation (SR) penetrates into the atmosphere, the ratio of PAR to SR (PAR/SR) increases (Moon, 1940). Other studies indicate that PAR/SR mostly falls between 0.45 and 0.50 and should be regarded as a region-dependent value (Udo and Aro, 1999). However, the most recommended PAR/SR is 0.5 (Monteith and Unsworth, 1990), so this ratio was used to estimate PAR from SR in this study. As another estimate of PAR, PAR/SR can be a simple function of the ratio of global to extraterrestrial SR, K\text{T} (Tsubo and Walker, 2004). The relationship at Bloemfontein, South Africa is as follows:

\[
\frac{\text{PAR}}{\text{SR}} = 0.150K_T^2 - 0.401K_T + 0.635 \tag{5}
\]

When K\text{T} equals 1.0, theoretically PAR/SR is 0.4 because energy in the wavebands between 0.4 and 0.7 μm is 40% of the solar constant (Monteith and Unsworth, 1990). Substituting K\text{T} = 1 into Eq. (5) gives 0.384 for PAR/SR. This confirms the theoretical PAR/SR ratio of 40%. PAR/SR is greater than 0.6 under very cloudy skies (McCree, 1966). PAR/SR calculated from Eq. (5) also gives higher values, up to 0.6, when K\text{T} has extremely low values.

3.2.2. Fraction of radiation intercepted

Tsubo and Walker (2002) describe a model of radiation interception through a cereal–legume intercrop canopy as follows. There are two canopy layers in cereal–legume intercropping, so the boundaries are determined by the canopy heights of the cereal and legume crops. When the cereal crop canopy is taller than the legume crop canopy, the upper turbid layer only comprises the cereal turbid medium while the lower turbid layer consists of both cereal and legume turbid mediums. The fraction of radiation intercepted by the cereal crop in the first turbid layer (F\text{C1}) is given by:

\[
F_{C1} = 1 - \exp(-K_C \times L\text{AI}_{C1}) \tag{6}
\]

<table>
<thead>
<tr>
<th>Crop</th>
<th>Cultivar</th>
<th>Growth period (days)</th>
<th>DD (°C d)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergence to flowering</td>
<td>Flowering to maturity</td>
</tr>
<tr>
<td>Maize</td>
<td>Short duration</td>
<td>125</td>
<td>629</td>
<td>744</td>
</tr>
<tr>
<td></td>
<td>Medium duration</td>
<td>145</td>
<td>709</td>
<td>843</td>
</tr>
<tr>
<td></td>
<td>Long duration</td>
<td>165</td>
<td>796</td>
<td>928</td>
</tr>
<tr>
<td>Beans</td>
<td></td>
<td>100</td>
<td>564</td>
<td>583</td>
</tr>
</tbody>
</table>

* Maize and bean DD values estimated from growth periods (days) reported by Allen et al. (1998) and the average DD from planting to emergence (=55 °C d) by Angus et al. (1981). Planting dates of 1 November, 15 November and 1 December were used to determine DD for long, medium and short duration maize cultivars, respectively, and 1 December was used for beans.
where LAI_{C1} is cereal leaf area index (LAI) in the upper turbid layer, and K_{C} is a cereal crop canopy extinction coefficient. Using the equation described by Keating and Carberry (1993), the fraction of radiation intercepted by cereal and legume in the lower turbid layer (F_{C2} and F_{L}, respectively) is given by:

\[
F_{C2} = \frac{K_{C} \times LAI_{C2}}{K_{C} \times LAI_{C2} + K_{L} \times LAI_{L} \\
\times [1 - \exp(-K_{C} \times LAI_{C2} - K_{L} \times LAI_{L})] 
\]

(7)

\[
F_{L} = \frac{K_{L} \times LAI_{L}}{K_{C} \times LAI_{C2} + K_{L} \times LAI_{L} \\
\times [1 - \exp(-K_{C} \times LAI_{C2} - K_{L} \times LAI_{L})] 
\]

(8)

where LAI_{C2} and LAI_{L} are cereal and legume LAI in the lower turbid layer, and K_{L} is a legume crop canopy extinction coefficient. Assuming that leaves are randomly distributed in the canopies, LAI_{C1} and LAI_{C2} can be calculated as follows:

\[
LAI_{C1} = (1 - \eta) \times LAI_{C} 
\]

(9)

\[
LAI_{C2} = \eta \times LAI_{C} 
\]

(10)

where \eta is the ratio of plant (or canopy) heights of legumes to cereals, and LAI_{C} is total cereal LAI.

Leaves increase their leaf angle (more vertical leaves) under soil water deficit, while adequate soil water results in little variation in leaf angle (Ehleringer and Forseth, 1989). Thus, the canopy extinction coefficient (K) may be dependent on soil water availability. However, from the data analysis, no clear relationship between K and plant extractable soil water was found (not shown). Therefore, in this study, a constant canopy extinction coefficient (K) over a crop growing season was estimated from a relationship between LAI and \ln(1 - F), as shown in Fig. 1a. These K values (maize: 0.432 and beans: 0.618) from the field experiment may be compared with those from Monteith (1969): 0.65 for maize and 0.80 for beans.

Individual plant leaf area (m^2 plant^{-1}) was estimated from total above-ground biomass (g plant^{-1}) during the vegetative stages (Fig. 1b). Initial biomass was set at 2.5 g for cereal crops and 0.5 g for legume crops. Leaf area and biomass multiplied by plant density gave LAI and TDM, respectively. Leaf area during reproductive stages was estimated using the senescence rate of green leaf area. The senescent rate was calculated on the basis of DD for the period from flowering to maturity. It was assumed that leaf area declines linearly after flowering time, when available soil water in 900 mm depth of soil is less than 50%. From linear regression analysis using the data collected in this study, the senescent rate was set at -0.0003 m^2°C d^{-1} for maize and -0.0008 m^2°C d^{-1} for beans.

There may be a shade effect on legumes intercropped with the taller cereal crops, causing a greater reduction in incident radiation (Stirling et al., 1990). However, \eta in intercropping may not differ from sole cropping. In this study, it was assumed that \eta is 1.0 at emergence and declines until flowering of the cereal crop, and \eta can be estimated from the reciprocal function of DD for the period from emergence to flowering (Fig. 1c). Another important assumption made was that cereal and legume crops are sown on the same date. Since DD to flowering of maize is greater than the DD for beans, the DD for maize was used to estimate \eta. From Table 2 and the equation given in Fig. 1c, \eta at flowering of maize was 0.346, 0.320 and 0.295 for short, medium and long duration maize cultivars.

### 3.2.3. Radiation use efficiency

There is a positive relationship between RUE and soil water availability under water stressed conditions, although RUE is constant under non-stressed conditions (Singh and Sri Rama, 1989). Assuming that there is no difference between vegetative and reproductive stages, RUE can be determined using an exponential function of available soil water (ASW), as shown in Fig. 1d. ASW on the i-th day is defined as:

\[
\text{ASW}_i = \frac{\theta_i - \theta_{WP}}{\theta_{FC} - \theta_{WP}} 
\]

(11)

where \theta_i is soil water content (mm) in 900 m depth of soil on the i-th day, and \theta_{WP} and \theta_{FC} are soil water content at wilting point and field capacity, respectively, for which lower limit and drained upper limit of available soil water (LL and DUL, respectively) are substituted. LL and DUL were set to 160 mm and 260 mm, respectively, for the Agrometeorology site while for the Soil Science site, 100 mm and 160 mm values were used.
Soil water content \( \theta_i \) is estimated using the water balance equation:

\[
\theta_i = \theta_{i-1} + RF_{i-1} + IR_{i-1} - ET_{i-1} - RO_{i-1} - DP_{i-1}
\]

where RF, IR, ET, RO and DP are rainfall, irrigation, evapotranspiration, runoff and deep percolation. ET was estimated using the combined model with the Ritchie (1972) method for soil evaporation and the transpiration coefficient approach (Tanner and Sinclair, 1983) for transpiration calculation. Coefficients for the Ritchie evaporation model from Jaafer et al. (1978) were used, and transpiration coefficients are 9.5 g kPa kg\(^{-1}\) for maize (Tanner and Sinclair, 1983) and 3.4 g kPa kg\(^{-1}\) for beans (Ogindo, 2003). RO was estimated using the Soil Conservation Service (SCS)-United States Department of Agriculture (USDA) runoff curve number method (USDA-SCS, 1986). A runoff curve number for row crops cultivated on sand, loamy sand and sandy loam soils with good infiltration of water into the soil was used for both experimental sites. DP may be estimated using water-holding capacity for a specific soil profile, however, in semi-arid regions, DP can be considered to be negligible.

An alternative simple model for estimating ASW was compared with the water balance model. The simple ASW model used in this study is the exponential
decay curve (Passioura, 1983; Monteith, 1986):

\[
\text{ASW} = \frac{\theta^* - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \exp(-\lambda t)
\]  

(13)

where \(\theta^*\) is the sum of rainfall and soil water content at the end of the previous decay cycle, \(\lambda\) is a decay coefficient and \(t\) is time (days) after starting the decay cycle. The decay curve starts at emergence and restarts every rainy day. Ogindo (2003) reported \(\lambda\) from 0.03 to 0.11, and in this study \(\lambda\) was set to 0.08.

4. Model validation

A total of eight combinations of variants in the intercrop model (Table 3a) were assessed in order to

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
<th>Model 5</th>
<th>Model 6</th>
<th>Model 7</th>
<th>Model 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component in sub-model</td>
<td>PAR(^a)</td>
<td>Var</td>
<td>Var</td>
<td>Var</td>
<td>Var</td>
<td>Const</td>
<td>Const</td>
</tr>
<tr>
<td>R(^b)</td>
<td>Exp</td>
<td>Exp</td>
<td>Lit</td>
<td>Lit</td>
<td>Exp</td>
<td>Exp</td>
<td>Lit</td>
</tr>
<tr>
<td>ASW(^c)</td>
<td>SWB</td>
<td>DC</td>
<td>SWB</td>
<td>DC</td>
<td>SWB</td>
<td>DC</td>
<td>SWB</td>
</tr>
</tbody>
</table>

(a) Components in sub-model

(b) Growth

Maize

| A | 113 | 192 | 204 | 396 | 125 | 289 | 220 | 522 |
| B | 1.01 | 0.99 | 1.16 | 1.07 | 1.11 | 1.04 | 1.23 | 1.11 |
| R\(^2\) | 0.80 (1) | 0.74 (5) | 0.77 (2) | 0.68 (6) | 0.77 (2) | 0.67 (7) | 0.76 (4) | 0.60 (8) |
| D | 0.91 (1) | 0.86 (3) | 0.81 (4) | 0.68 (7) | 0.87 (2) | 0.75 (5) | 0.75 (5) | 0.58 (8) |
| MBE | 119 (1) | 186 (3) | 283 (4) | 429 (7) | 182 (2) | 309 (5) | 350 (6) | 574 (8) |
| RMSE | 196 (1) | 258 (2) | 347 (4) | 486 (7) | 263 (3) | 383 (5) | 424 (6) | 640 (8) |

Beans

| A | 42 | 54 | –2 | 5 | 50 | 87 | 7 | 29 |
| B | 0.73 | 0.98 | 0.89 | 1.28 | 0.75 | 1.08 | 0.90 | 1.41 |
| R\(^2\) | 0.40 (7) | 0.50 (2) | 0.43 (5) | 0.51 (1) | 0.40 (7) | 0.48 (3) | 0.42 (6) | 0.48 (3) |
| D | 0.80 (1) | 0.80 (1) | 0.79 (3) | 0.74 (6) | 0.79 (3) | 0.73 (7) | 0.79 (3) | 0.67 (8) |
| MBE | –15 (3) | 50 (5) | –25 (4) | 63 (6) | –1 (1) | 103 (7) | –14 (2) | 112 (8) |
| RMSE | 196 (1) | 258 (2) | 347 (4) | 486 (7) | 263 (3) | 383 (5) | 424 (6) | 640 (8) |

(c) Yield

Maize

| A | –48 | 98 | –67 | 184 | –85 | 160 | –77 | 252 |
| B | 1.07 | 0.79 | 1.16 | 0.77 | 1.12 | 0.77 | 1.19 | 0.75 |
| R\(^2\) | 0.62 (4) | 0.62 (5) | 0.65 (2) | 0.54 (7) | 0.66 (1) | 0.55 (6) | 0.64 (3) | 0.47 (8) |
| D | 0.86 (4) | 0.88 (1) | 0.87 (2) | 0.84 (7) | 0.87 (2) | 0.85 (5) | 0.85 (5) | 0.78 (8) |
| MBE | –15 (3) | –5 (1) | 10 (2) | 71 (7) | –24 (5) | 46 (6) | 17 (4) | 128 (8) |
| RMSE | 183 (5) | 143 (7) | 135 (3) | 187 (6) | 178 (5) | 180 (4) | 168 (2) | 200 (7) |

Beans

| B | 0.61 | 1.23 | 0.67 | 1.45 | 0.56 | 1.38 | 0.72 | 1.61 |
| R\(^2\) | 0.62 (7) | 0.73 (2) | 0.64 (6) | 0.75 (1) | 0.47 (8) | 0.70 (4) | 0.66 (5) | 0.72 (3) |
| D | 0.89 (6) | 0.89 (1) | 0.69 (6) | 0.86 (2) | 0.68 (8) | 0.85 (3) | 0.70 (5) | 0.83 (4) |
| MBE | –103 (6) | –15 (2) | –107 (8) | –22 (4) | –90 (5) | 16 (3) | –105 (7) | 1 (1) |
| RMSE | 120 (6) | 82 (1) | 124 (8) | 100 (2) | 112 (4) | 101 (3) | 121 (7) | 119 (5) |

A, the intercept of fitted line; B, the slope of fitted line; R\(^2\), the coefficient of determination; D, the index of agreement; MBE, mean bias error (unit: g m\(^{-2}\)); RMSE, root mean square error (unit: g m\(^{-2}\)). Numbers in parentheses are rank within rows. Big values of R\(^2\) and D, and small absolute values of MBE, and small values of RMSE indicate that the models are good.

\(^a\) Var, the variable PAR/SR; Const, the constant PAR/SR.

\(^b\) Exp, K from the experiment; Lit, K from the literature.

\(^c\) SWB, the soil water balance method; DC, the decay curve method.
determine the best combination of sub-models and coefficients from the following factors:

(i) PAR/SR: variable PAR/SR (Eq. (5)) or constant PAR/SR (=0.5);
(ii) $K$: field experiment (0.432 for maize; 0.618 for beans) or literature (0.65; 0.8) (Monteith, 1969); and
(iii) ASW: soil water balance (Eqs. (11) and (12)) or decay curve for soil water content (Eq. (13)).

For model validation, the correlation-based statistic, i.e., coefficient of determination ($R^2$), was used together with the deviation-based statistics, i.e., mean bias error (MBE), root mean square error (RMSE) and the index of agreement ($D$) (Willmott, 1981). The model was evaluated using both sole cropping and intercropping systems with TDM data at flowering time (between 50 and 70 DAP) for growth and at maturity time (between 100 and 140 DAP) for yield since TDM of leaf + stem and $Y$ reached maximum values on the $k$-th day and $n$-th day, respectively.

The correlation-based and deviation-based statistics for the model performance for growth are presented in Table 3b. The models had $0.60 \leq R^2 \leq 0.80$ for maize growth and $0.40 \leq R^2 \leq 0.51$ for bean growth. The $D$-index varied between 0.58 and 0.91 for maize and between 0.67 and 0.80 for beans. By ranking the statistics, the best model for both intercropped and sole cropped maize growth was Model 1, while Model 2 gave the same representation of the growth of beans. With respect to yield, the $R^2$ varies between 0.47 and 0.66 for maize and 0.46 and 0.75 for beans. The $D$-index is above 0.78 for maize and 0.68 for beans, and MBE and RMSE were less than absolute values of 130 and 230, respectively.
By ranking the statistics, Model 2 was chosen as the best model for yield estimation of both maize and bean crops. Therefore, based on the above results, Model 2 performed better overall than the other models. Fig. 2 shows examples of the seasonal changes in the model output for Model 2 and the actual field measurements. The calculated TDM of intercropped and sole cropped maize during the 1999/2000 season (under irrigation) generally agreed with the measured data. However, under rainfed conditions (2001/2002 season), the model overestimated the TDM in the vegetative stage and underestimated it in the reproductive stage. The model also overestimated TDM of sole beans during both growth stages. Fig. 3 illustrates the relationship between the measured and modelled TDM at flowering time (a) and grain yield at maturity (b) for Model 2. The data points for yield are evenly scattered around the 1:1 line, while there was an overestimation of TDM. The model estimation was less accurate when yield was less then 250 g m\(^{-2}\) for beans (\(R^2 = 0.31; D = 0.70; MBE = -31; RMSE = 63\)) and 700 g m\(^{-2}\) for maize (\(R^2 = 0.22; D = 0.65; MBE = 16; RMSE = 154\)).

Many studies have confirmed that PAR/SR changes from low to high as sky conditions vary from clear to cloudy (McCree, 1966). In terms of incident SR on the surface of the earth, cloudiness is often quantified using the ratio of diffuse to global SR. As the clearness index decreases, the diffuse to global SR ratio increases (Tsubo and Walker, 2003), so daily variation in PAR/SR can be explained by the clearness index (Tsubo and Walker, 2004).

Many studies report differing canopy extinction coefficients (Campbell and Norman, 1998), with these differences probably reflecting differences in soil water, plant nutrition, incident radiation, canopy architecture (inter- and intra-row spacings) and plant population. Greater values of \(K\) (i.e. from literature) mean that leaves tend to be more horizontal, resulting in greater radiation interception by canopies. Thus, the PAR interception sub-model with canopy extinction coefficients from the literature can give greater values of PAR interception than that with the extinction coefficients from the field experiment. Tsubo and Walker (2002) have recently validated the latter in the study region.

The framework for analysis of water extraction, using the decay curve, was initially developed by Passioura (1983) and Monteith (1986). The decay curve approach has been adopted in a number of studies involving soil water extraction (Robertson et al., 1993; Singh et al., 1998; Ogindo, 2003) and has been found to perform best under conditions where the crops grow with predominantly stored soil water, as in semi-arid regions. The approach is based solely on the capacity of the root system to extract stored soil water, whereby the rate of transpiration is likely to be limited by the rate of water extraction. It greatly simplifies the amount of information needed to estimate available soil water (Eq. (13)) as opposed to the alternative

![Fig. 3. Comparison of the measured and modelled values of (a) maize and bean total dry matter (TDM) and (b) maize kernel and bean seed yields using Model 2. TDM data was not available for the 1997/1998 season.](image-url)
approach (Eqs. (11) and (12)). This is based on the fact that only the decay coefficient \( \lambda \) need be determined for different sites and soils. However, the choice of this value for the decay coefficient is critical in obtaining an accurate soil water balance. The validation results for the two sub-models confirm the better performance for yield of the decay curve approach as compared to the alternative water balance approach. On the other hand, the soil water balance method also has a number of components, each of which have the potential for introducing errors to the final outcome of the simulation by the sub-model. From the above results (see also Table 3b and c), the combination of the variable \( \text{PAR/SR, K} \) based on the field experiment and the decay curve for the soil water content (Model 2) proved to be the best of all eight models for the sites considered.

5. Conclusions

The intercrop model was developed to estimate crop growth and yield in maize–bean intercropping under semi-arid climate conditions. The selected model performed reasonably well for yield of both crops, although the model prediction for growth (at maximum level of leaf + stem biomass) was not as accurate as that for yield. Effects of nutrients stress on intercropping were not considered in the model, but water stress effects on RUE were incorporated. Due to more limited development of the lateral root systems of both maize and beans under rainfed conditions (relative to irrigated cropping) there may be less competition for water between maize and beans in intercropping situations. Therefore, the model dealt only with competition for light, not for water. Canopy architecture (row arrangement and orientation) was not taken into account, but canopy height was built into the model as a two-layer canopy model. In the model development, three modules of the model were evaluated—\( \text{PAR, K and ASW} \). The combination of \( \text{PAR} \) estimated from the clearness index, a crop extinction coefficient determined from the field experiment and the decay curve model for available soil water in the root zone gave the most sound and acceptable outcomes. The \( \text{PAR–K}_T \) relationship (Eq. (5)) estimates \( \text{PAR} \) more accurately than the constant \( \text{PAR/SR} \) because of variable sky conditions from clear to cloudy. In simple radiation-based crop growth models, canopy extinction coefficients determined in different environments, can lead to inaccurate estimates of radiation interception by crops, implying that canopy extinction coefficients are conservative. The decay curve model (Eq. (13)) performs better than the water balance model, resulting in minimal inputs and coefficients for estimating soil water. The intercrop model developed in this study is relatively simple, so this model development technique can be employed to build other cereal–legume intercrop models for semi-arid regions. In terms of risk assessment of crop production, the model can be used to evaluate long-term cereal–legume intercrop yields in semi-arid regions. In a separate paper (Tsubo et al., 2005), the best model (Model 2) has been used to simulate long-term maize–bean intercrop yields in the semi-arid region.

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