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Input levels and intercropping productivity: exploration by simulation

A.M. Wubs, L. Bastiaans & P.S. Bindraban

Note 369

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Voorwoord

Aan het einde van mijn studie (najaar 2004) benaderde Lammert Bastiaans mij met de vraag of ik een studie wilde doen naar intercropping bij verschillende inputniveaus m.b.v. simulatiemodellen. Dit leek me een leuke uitdaging voor na mijn afstuderen en ging aan de slag. Voor u ligt daarvan het resultaat: een voorstudie van het effect van verschillende niveaus van waterinput op een sorghum-cowpea intercrop. Ik heb er met veel plezier aan gewerkt, nieuwe dingen bij geleerd en hoop dat het onderwerp een vervolg zal krijgen.
Ik wil hierbij graag mijn begeleiders Lammert Bastiaans en Prem Bindraban bedanken voor het mogelijk maken van deze studie en voor de nuttige tips en discussies die we in de afgelopen maanden hebben gehad.

Maaike Wubs

Wageningen, 31-10-2005

1. Context of the project

1.1 Introduction

On the 25th of June 2004, a plan to deal with hunger in Africa was presented at the headquarters of the United Nations in New York. It was compiled by the Inter Academic Council (IAC) and it gave a set of concrete steps for diminishing the undernourishment in Africa. Undernourishment in Africa is much higher than in the rest of the world (Figure 1.1) and thus needs good points for action. According to the authors, it is possible for Africa to increase the agricultural productivity, improve the food security and enhance the sustainability of agro-ecosystems (Anonymous, 2004).

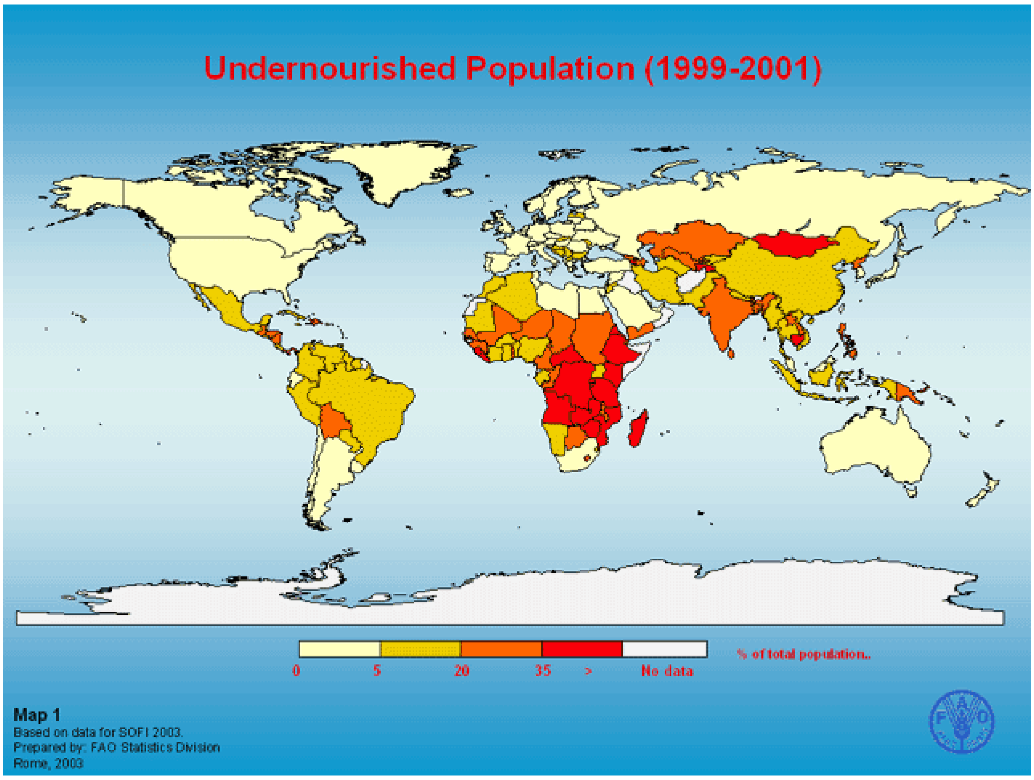

Figure 1.1. World map indicating percentage of undernourished people in the total population per country (source: FAO, 2003).

Definitions

Undernourishment is defined as the state of a person whose dietary doesn't contain the energy needed for his of her active and healthy life (FAO, 2003).
The definition of food security is given by the World Food Summit as 'all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (FAO, 1996). Thus, by ensuring food security, undernourishment will be eliminated.
Food security has three dimensions which have to be met: availability, access and stability. The availability of the food has to do with the production level and is of primary importance. The access deals with the infrastructure for distribution of the food, ability to buy food (food prices, income) and utilisation of the food and finally, the stability of food security has to do with the temporal variations in the availability and access to food (Flores, 2004).

Below, a very short description of the food production situation in Africa is given. Next, the trends relating to food (in-) security are described, followed by the reasons for the insufficient production levels (and thus undernourishment). This leads to the aim of this project, which is given in the last paragraph.

1.2 Production situation in Africa

Of the total African population, 812.6 million people, 62% live in the rural areas. The agricultural labour force is 200.4 million people. In 2001, the total arable land consisted of 182.3 million hectares (6% of the continents land), from which 26.3 million hectares is permanently cropped. The input per hectare is low; in the whole of Africa on average 22 kg nutrients per hectare were given in 2000-2001, for sub Saharan Africa this was just 9 kg per hectare. 7% of the arable land was irrigated (FAO, 2003). Derived from above, the labour force is 1.09 per hectare arable land. Mechanisation is low: most work is done by hand with simple tools or with animals (FAO, 1983), even today.

Most of the farmers are smallholders. Steiner (1982) reported that 80-90% of the farmers have a farm with 1-2 hectareland. FAO (1983) gives a size of 2 ha for farms in West Africa. Tessema (www.nlh.no) reported that only 2 out of 142 households in his study area Gununo, Ethiopia have more that 2 hectares. Mkhabela and Materechera (2003) reported an average farm size of 2.9 ha for small farmers in the Midlands of KwaZulu-Natal in South Africa. This small holder farming is mainly subsistence farming, where the whole family is working on the farm. The farmer grows what he needs and the diversity of crops is high. Off-farm employment supplements their income.

On these small farms, intercropping is common practise. Steiner (1982) mentioned seven basic crops for mixed cropping systems in Western Africa: cassava, plantain, yam, rice, sorghum, millet and maize. Common crops in the area associated with the basic crops are sweet potato, okra, cocoyam, soybean, chickpea, pigeon pea and groundnuts. Tree crops which can be found are coconut, cocoa, oil palm and fruit trees (Steiner, 1982; FAO, 1983). Some cash crops like cotton and sugar cane are grown in pure stands (FAO, 1983).

1.3 State of undernourishment in Africa: past, present and future

The present state of food security in Africa is low. The continent has the highest percentage undernourished people in the world, 28% in 1998-2000, while Asia had 16% and Latin America and the Caribbean 11%. Of the population of sub-Saharan Africa, even 33% is undernourished (198.4 million people). The percentage of undernourishment has decreased over the past decades, from 34% in 1969-1971, via 31% in 1979-1981 and 29% in 1990-1992 till the current level (FAO, 2003), but the absolute number increased (FAO, 2004). The total food production in Africa had an annual growth rate of 2.9% over the last ten years, but the growth rate of food per capita was close to zero. The value of the production per agricultural worker increased over the last twenty years, as did the production per hectare arable land (FAO, 2003; FAO, 2004).

For the future, the population of Africa is expected to grow at an average annual growth rate of 2.3% between 2000 and 2010 and the growth rate will decrease to 1.3% in the period between 2040 and 2050. This will eventually lead to a population of 2 000 million people in 2050. Projections of the food production are positive, which causes a decrease in the percentage undernourished people in Africa to 13% (189 million people) in 2030. The arable land in Africa is expected increase to 315 million hectares in 2030. However, through the growing population, the hectares of arable land per person will decrease, which means that the production per hectare will have to increase in order to keep up with the growth in food demand. The number of agricultural labour force per hectare is expected to be 0.73 in 2030 (FAO, 2003), which implies that also the production per labour force will have to increase.

1.4 Causes of low production

Low production levels in Africa have a number of causes. They can be either environmental or human causes. Steiner (1982) gives low soil fertility, labour shortage, unpredictability of rainfall, lack of cash resources and limited access to credits as major causes. Flores (2004) reports (besides conflicts) poverty, natural disasters and gender discrimination as causes of food insecurity. The IAC learned that among others, low investment in agriculture, poor irrigation systems, a wide variety of crops and a lack of knowledge due to brain drain are causes of low productivity (Anonymous, 2004). Catastrophic natural disasters are usually difficult to forecast and add to the causes for acute food insecurity. An example is the desert locust, which dynamics are difficult to forecast and which are currently devastating crops in Northern Africa.

Conflict situations add to the state of food insecurity. Civil strife and/or the existence of displaced people are one of the causes of food insecurity in half the reported food emergencies in Africa. The occurrence of a conflict decreases the food availability during as well as after the conflict (Flores, 2004).

In the last three decades, the HIV/AIDS epidemic is added to the causes. Apart from decrease in labour availability and increase in labour costs (through scarcity) caused by HIV/AIDS, also the decline of practical agricultural knowledge may play an important role (Jayne *et al.*, 2004).

1.5 Overall aim of the project

From the above mentioned it can be learned that one aspect that is required in order to ensure food security is an increase in total food production and productivity per unit input, primarily land and labour. Farming systems in Africa are mainly small holder farms which apply mixed farming or intercropping. Generally, it is believed that intercropping systems are especially effective when input levels are low (FAO, 1983; Bindraban, pers. comm.), but that the advantage decreases as inputs increase. From projections we saw that the production per hectare as well as the labour productivity has to increase. Increase of production per hectare is commonly realised by increasing the input levels. An important question is what influence this has on the cropping system? Are intercrops still advantageous at high input or will it be better to switch to pure stands? In other words: should the increase in production be achieved through the traditional intercropping systems, or should high input monoculture systems be adopted?

In this project, a preliminary study was undertaken to examine this question. Simulations for pure stands and intercropping situations were done at different levels of water supply and the results of production, water use and water use efficiency were studied. This was done with the help of a simple simulation model, which accounts for competition for light and water between component crops. Also variations in plant traits and agronomic practices were introduced to assess the impact on productivity.

In the next chapter, different aspects of intercropping are described to get an insight in intercropping: basic features, measures of effectiveness, practice in Africa and the western world, advantages and disadvantages. In the third chapter, a simple simulation model which is developed for the simulation studies is described. With this model, explorations were made for different agronomic situations (densities, pure stands and intercrops, and different levels of water supply) and plant traits (e.g. variation in plant height, radiation use efficiency and time of emergence). The results are presented in chapter 4, 5 and 6. The productivity of the simulation results of pure stands and intercrops will also be compared at different input levels to see if certain trends can be distinguished. At the end, conclusions about the productivity in the different cropping systems are made on basis of the simulation results and what this implies for food production in Africa.

2. Background information about intercropping

In this chapter, some basic aspects of intercropping are described. It is not the scope of this chapter to describe the mechanisms occurring in intercropping, but merely to give an overview of its features, the measures for productivity of intercropping, its use in practice and the advantages and disadvantages.

2.1 Definition and features of intercropping

Intercropping means growing different crops or different varieties of one crop simultaneously on the same piece of land (Ranganathan, 1993; Vandermeer, 1989; Steiner, 1982).
When growing two or more crops on the same field, the density of the intercrop can have the same density as a sole crop (replacement intercropping) or the density of the corps is the sum of the densities of the sole crops (additive intercropping) (Ranganathan, 1993; Keating and Carberry, 1993).
The spatial pattern of the crops can be arranged in several ways (Steiner, 1982):

- Mixed intercropping: no special pattern is given to the crops
- Intra-cropping: different species are altered within the rows
- Row intercropping: altering 1 or 2 rows of one crop with another crop
- Strip intercropping: crops growing in broad strips, several rows wide
- Multi-storey intercropping: tall perennial with shorter biannual or annual crops (mainly occurring in agroforestry)

Besides difference in density and spatial pattern, there can also be differences in timing of the crops (Keating and Carberry, 1993). One of the crops can be sown later than the other, thus giving the first crop the time to develop. Sowing the second crop when the first crop is nearly mature is called relay intercropping (Beets, 1982). Another example is sowing a fast developing crop with a slow developing crop and in this way making optimal use of the growing season (Steiner, 1982).
The competition for resources between the crops in an intercropping system can be non-competitive, competitive or complementary (Steiner, 1982). In a non-competitive situation, the crops share the growth factors to such an extent that resource supply is not limiting the growth of the crops. Complementarity can then exist when the two crops have different needs for the different resources and so make better use of the available resources. A competitive situation exists when the crops compete for the same resource(s) and the interspecific competition is equal or higher than the intraspecific competition (Davis and Woolley, 1993). In one intercropping system, both competition and complementarity situation can exist, for example competition for light but complementary for nutrients or a system can be complementary in the early phase of crop growth, but become competitive in a later stage (Midmore, 1993). For the environmental conditions, facilitation can occur: one crop improves the environmental conditions for the other crop, for example by providing growing space or preventing the spread of pests (Vandermeer, 1989).

2.2 Measures for intercropping effectiveness

The productivity of an intercropping system in comparison to monoculture is usually measured with the Land Equivalent Ratio (LER), which is given by the following formula (Fukai, 1993):

$$LER = \sum_{j=1}^{n} y_{j,i} / y_{j,s} \qquad \text{equation 2.1}$$

Where $y_{j,i}$ is the yield of component crop j in intercropping and

$y_{j,s}$ is the yield of component crop j in sole cropping

A LER value of more than one indicates an advantage of intercropping over sole cropping on basis of land use. It is used for additive series, where the density varies. A comparable measurement is the Relative Yield Total (RYT), which is calculated in the same way but is used for replacement series where the total density is kept the same but the proportions of the components vary (Baumann, 2001). Vandermeer (1989) uses the LER for additive and replacement intercropping. The LER and RYT can not only be expressed in weight of yield, but also in the amount of proteins, fat or carbohydrates yielded.
For resources like light, water and nutrients, the production consists of two factors: the capture and the utilisation efficiency of the resource. For water this can be described by:

$$CP = WU * WUE \qquad \text{equation 2.2}$$

Where CP is the crop production (dry weight / unit area)
WU is the water use (unit mass of water uptake / unit area)
WUE is the water use efficiency (dry weight / unit mass of water uptake)

To compare differences in sole cropping and intercropping, the following formula's can be used for water use and water use efficiency (Morris and Garrity, 1993a):

$$\Delta WU(\%) = ([WU_{ic} / (P_a WU_{sa} + P_b WU_{sb})] - 1) * 100\% \qquad \text{equation 2.3}$$

Where WU_{ic}, WU_{sa} and WU_{sb} are the water use in intercropping, sole cropping species A and sole cropping species B, respectively
P_a and P_b are proportions of species A and B in the intercrop, given by $P_a = D_a / (D_a + D_b)$
with D_a and D_b the density in intercropping relative to sole cropping of species A and B, respectively

$$\Delta WUE(\%) = (\{[Y_{ic} / WU_{ic}] / [(P_a Y_{sa} / WU_{sa}) + (P_b Y_{sb} / WU_{sb})]\} - 1) * 100\% \qquad \text{equation 2.4}$$

Where Y_{ic}, Y_{sa}, Y_{sb} are the yields in intercropping and sole cropping of species A and B respectively

When ΔWU and ΔWUE are greater than zero, the water use and the water use efficiency are higher in the intercrop than in sole cropping. Similar formula's can be used for the uptake and use of phosphorus, potassium and other nutrients (Morris and Garrity, 1993b). For light, success of an intercrop also depends on the difference in light interception and light use efficiency between the crops, but formula's to measure this are not common.

2.3 Intercropping in practice: Africa and the Western world

Intercropping is a common practice in Africa. It is mostly practised on small farms, where there is a limited production capacity, due to lack of capital to acquire inputs. The features of an intercropping system differ with soil, local climate, economic situation and preferences of the local community. Local varieties are used for intercropping, which have been selected over the years for this purpose (Steiner, 1982).
African farmers use different combinations in intercropping. In the first situation, the farmer plants a crop at normal density to obtain full yield and a second crop at low density to obtain a 'bonus' yield. In the second situation, an intercrop is planted at the optimum stands for both crops to obtain as much yield as possible from both crops (Steiner, 1982).
The common crop combinations in intercropping are grain and legumes or a root crop and a legume. Common combinations of crops are maize and soybeans, rice and pulses, maize and cowpea (Beets, 1982), sorghum and cowpea (Rees, 1986a,b), cassava and pigeonpea (Cenpukdee and Fukai, 1992). These mixtures are also often a combination of a C_3 and a C_4 crop. Intercropping combinations with trees (coconut, rubber and oil palm) can occur with crops like ground nuts, sweet potatoes and papaya (Beets, 1982).

The farmers, who mostly have low access to resources, can optimise their intercropping system by choice of crops, site and timing of planting, spatial pattern and plant densities (Midmore, 1993).

In the western world with high inputs and a high level of mechanisation, intercropping is not a common practice. Grasslands which contain a combination of grasses and clovers are a common intercrop in the western world. They are often productive for more than one season, in contrast to African intercrops. Recently, intercropping gained increased attention, because of advantages in weed and pest suppression. Intercropping of leek and celery proved to be sufficient for weed suppression, while producing two valuable cash-crops (Bauman, 2001). In the US, strip intercropping is practiced, where several rows of one crop are alternated with several rows of another crop and in this way allow mechanical field operations (Steiner, 1982; Ghaffarzadeh, 1999). In Iowa, strip intercropping occurs with maize, soybeans and oats or other small grains (Ghaffarzadeh, 1999). In Australia, intercropping exists on a small scale. Perennial lucerne is intercropped with cereals for human or animal consumption (Harris *et al.*, 2003).

2.4 Advantages and disadvantages of intercropping

In social-economic perspective, a major reason for intercropping by African farmers is the stability of the yields over several seasons, and not the higher yield in one year (FAO, 1983; Steiner, 1982). The unpredictability of rainfall is one of the important factors which make intercropping more reliable to farmers. When one crop fails, the other might still give a reasonable yield (Ranganathan, 1993; Beets, 1982; Steiner, 1982). Two other reasons are the combination of higher diversity of crops and higher production in intercropping, resulting in more variation in the diet of the farmers (Beets, 1982; FAO, 1983) and the greater flexibility for management practices (FAO, 1983).
In agronomic respect, one of the important characteristics of intercropping is the more efficient use of growth factors: intercrops capture more radiation and make better use of the available water and nutrients. Intercropping is also said to reduce pests, diseases and suppress weeds and favours soil-physical conditions.
The light interception of an intercrop is higher, due to earlier ground cover. When the intercrop consists of a fast and slow maturing crop species, the radiation in the growing season is used more efficiently (Keating and Carberry, 1993).
Literature reviews show that the interception/uptake of the resources radiation and water is not only higher, but that these production factors are used more efficiently in the intercrop (Keating and Carberry, 1993; Morris and Garrity, 1993a). In contrast, the use of the nutrients P and K is usually higher in intercrops, while their efficiency is lower (Morris and Garrity, 1993b). Intercropping with legumes increases the nitrogen pool in the soil, which is available to the consecutive crop or to a slow maturing component crop (Stern, 1993).
It is also said that intercrops give a reduction in the occurrence of pests and diseases, but there are contrasting references for this (Trenbath, 1993; Steiner, 1982). Weed suppression is an advantage which is important in Africa as well as in the Western world. Through earlier ground cover, weeds have less opportunity to germinate and grow (Bauman, 2001).
Additional soil-physical advantages of intercropping are the reduction of soil erosion and increased infiltration of rainfall. The soil temperature under intercrops is lower, while the moisture content is higher (Olasantan, 1988), probably due to lower evaporation (Keating and Carberry, 1993). A lower soil temperature can be beneficial, since it decreases the rate of decomposition of organic matter and in this way increases soil fertility (Steiner, 1982). Higher crops in the mixture may also shelter wind for the other crop species, favour the microclimate and reduce lodging (Ghaffarzadeh, 1999; Steiner, 1982).

One of the major disadvantages is the difficulty of mechanisation. Machines for sowing, weeding, fertilising and harvesting are made for big uniform fields. In Africa, the work needed in the field is mainly done by hand with simple tools and for that reason very labour intensive. Labour is cheap, which makes it less desirable to invest in expensive machines (Vandermeer, 1989). For intercropping on a large scale, mechanisation is generally believed to be impossible, although examples of intercropping with modern machines do exist (Bauman, 2001; Ghaffarzadeh, 1999).

2.5 Theory about intercropping and input levels

A theory about intercropping and input level says that the productivity of intercropping systems is higher than for pure crop situations when the input is low, but that this advantage decreases as the inputs increase (FAO, 1983; Bindraban, pers. comm). This is visualised in Figure 2.1.

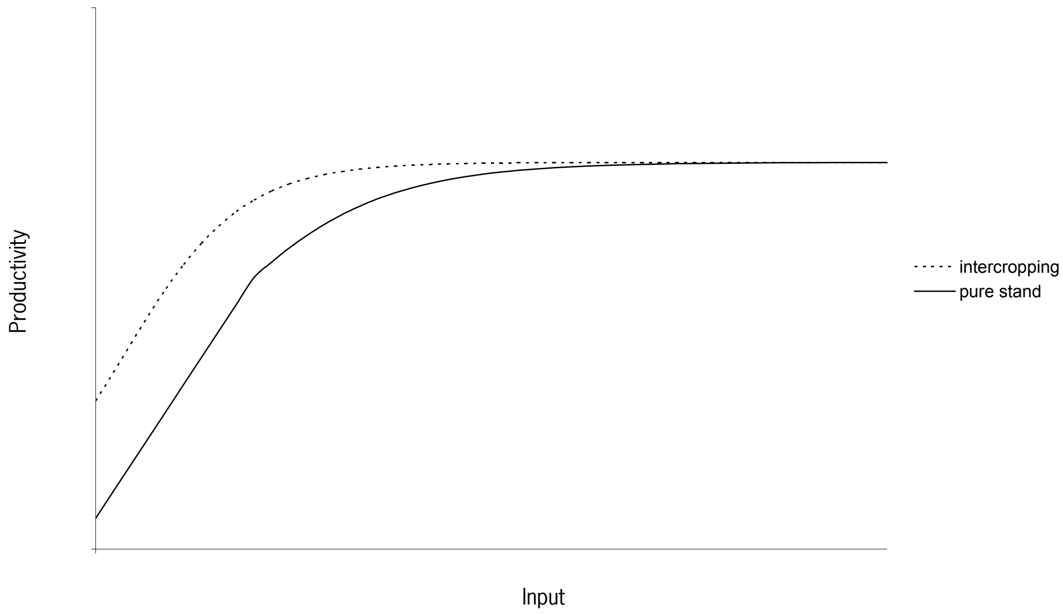

Figure 2.1. Graph showing the hypothesis of inputs and productivity in intercropping and pure stand.

As written before, intercropping makes more efficient use of the resources, which is especially important at low levels of input, and consequently an intercrop generates more yield at low input levels than pure stands. The advantage of efficient use of resources becomes less important as the resource is available in higher amounts. The productivity of the intercrop will level off towards the productivity of the pure stands. At a certain level of input, the advantage is not present any more and it will make no difference whether an intercrop or pure stands are sown.
To avoid scales of the absolute productivity, the productivity of intercrop and pure stands can be compared by taking the ratio of the productivity of the intercrop and the pure stand. If this ratio is higher than one, the intercrop has a higher productivity than the pure stand and if it is lower than one, the pure stand has a higher productivity. If the theory is right, the ratio of the productivities of intercrops and pure stands should get a value higher than one at low input levels and should become one (or close to one) at the higher levels of resource input. It could even be that the pure stand becomes more productive (ratio below one) or that the intercrop is more productive at any level of resource supply (ratio always above one). Results of intercrop experiments can be plot in graphs (see Figure 2.2) to see if the theory present in practice.

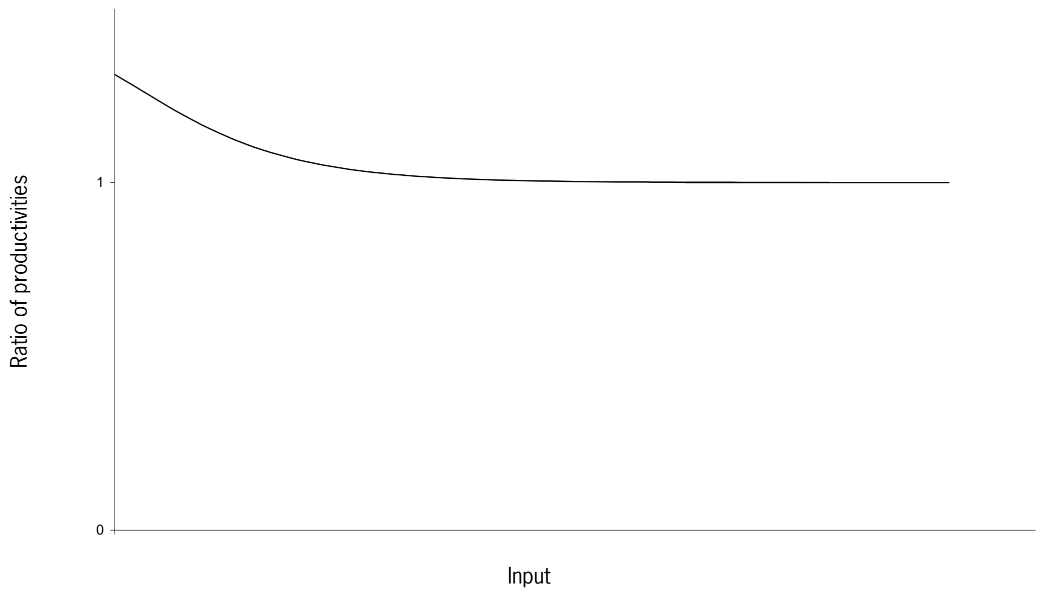

Figure 2.2 *The trend in the difference between the productivity of intercrops and pure stands as input increases, according to the hypothesis.*

3. Model description, parameterisation and overview of simulations

3.1 Model description

General

The model was made with the simulation programme FST. A basic description of FST is given in Rappoldt and Van Kraalingen (1996). Effort was made to keep the model as simple as possible and to minimize the number of parameters. The time step of the model is one day and the Euler integration method was used. Nutrients were assumed to be non-limiting and weeds and pests were absent.
In the description, common methods like Beer's law are not explained, only the more complicated and not generally known parts. Capitalised lines are codes from the model. The complete code of the model is given in Appendix I and the list of all the abbreviations of the model in Appendix II. The first part of this chapter describes the model. In the second part, parameters values and their source are given and in the last part, the conducted simulations and the presentation of the output are described.

Selection of the cropping system

Intercropping often occurs with a combination of a cereal and a legume (Beets, 1982; Ofori and Stern, 1987 in: Tsubo and Walker, 2002). A sorghum (*Sorghum bicolor* L.) -cowpea (*Vigna unguiculata* L.) intercrop was selected as an example of such an intercropping system. Both are well-known crops, so parameter values were easy to obtain and sufficient references are known for this intercropping (for example Gilbert *et al.*, 2003; Rees, 1986a,b; Lightfoot and Tayler, 1987; Morris *et al.*, 1990). In the model, sorghum is crop 1 and cowpea crop 2. All variables having suffix 1 refer to sorghum and variables with suffix 2 refer to cowpea.
The intercrop is grown on a loamy soil, where sorghum-cowpea experiments in Africa are often laid out (Tefera and Tana, 2002; Gilbert *et al.*, 2003; Craufurd, 2000). Crop growth is simulated between emergence and physiological maturity.

Plant development and growth

Development

The development of both crops is divided in a vegetative and a generative stage. A temperature sum is defined which was needed to complete each of the two stages. On every day, the cumulative temperature sum is calculated (TSUM). The gain in temperature sum (RTSUM) per day is calculated as the average of the minimum and maximum temperature (TA) minus the base temperature (TBASE). For sorghum, an alternative calculation is used when the average temperature is between the optimal and maximum temperature for development (TOPT and TMAX, respectively) (Hammer *et al.*, 1993; equation 3.1).

```
RTSUM1=INSW(TA-TOPT1,TA-TBASE1,(TOPT1-TBASE1)*(1.-(TA-TOPT1)/...
(TMAX1-TOPT1)))                                              equation 3.1
```

The development stage is calculated each day with the gain in temperature sum. The change of development stage (RDEV1) is the gain in temperature sum (RTSUM) multiplied with the inverse of the temperature sum needed to complete the vegetative or generative stage (for sorghum, TSUM11 and TSUM12, respectively). When the development stage is 2.1, development is completed and growth stops (equation 3.2a-c).

DEV1=MIN(DEV11,2.1) equation 3.2a
DEV11=INTGRL(IDEV,RDEV1) equation 3.2b
RDEV1=RTSUM1*INSW(TSUM1-TSUM11,1./TSUM11,1./TSUM12) equation 3.2c

Dry matter accumulation and plant growth

From the start of the plant growth, the growth is driven by light interception. The exponential growth determined by temperature does not take place, but the first phase of growth can be considered as exponential: only light is determining growth and no competition takes place.
The light interception is calculated according to Beer's law. Calculation of the distribution of the intercepted radiation over the two crops, which have a different height, is done according to Tsubo and Walker (2002). In this method, leaves are assumed to be evenly distributed over plant height. The height of the sorghum is always higher than the height of the cowpea (see Figure 3.3). The canopy is therefore divided into two layers. In the top layer only leaves of sorghum can be found and in the lower layer leaves of both sorghum and cowpea are found. The division of the LAI of sorghum over the two layers was proportional to the share of the height of each of the two layers in the total sorghum height (equation 3.3a, b).

LAIS1=(HEIGH1-HEIGH2)/HEIGH1*LAI1 equation 3.3a
LAIS2=HEIGH2/HEIGH1*LAI1 equation 3.3b

HEIGH1 and HEIGH2 are the height of the sorghum and cowpea plants, respectively. LAIS1 and LAIS2 are the leaf area index of sorghum in the upper and lower layer, respectively. Radiation in the upper layer is solely intercepted by LAIS1 (equation 3.4).

IINT11=I0*(1.-EXP(-K1*LAIS1)) equation 3.4

Radiation in the lower layer, where two crop species are present, is intercepted by

I0*EXP(-K1*LAIS1)*(1.-EXP(-K1*LAIS2-K2*LAI2)) equation 3.5

I0*EXP(-K1*LAIS1) is the radiation not intercepted by the sorghum leaves in the upper layer. The total intercepted radiation in the lower layer is divided over the species according to their share in the total effective leaf area (equation 3.6a, b).

K1*LAIS2/(K1*LAIS2+K2*LAI2) equation 3.6a
K2*LAI2/(K1*LAIS2+K2*LAI2) equation 3.6b

Equation 3.6a and 3.6b are for sorghum and cowpea, respectively. The total amount of radiation intercepted by the sorghum, IINT1, is calculated as total of the light interception in both layers. The total intercepted radiation of cowpea is called IINT2.

Then, potential growth rate (GROPO) was calculated as the intercepted light multiplied with the light use efficiency (LUE):

GROPO1=IINT1*LUE1 equation 3.7

To account for water stress, a variable called WATER (a fraction between 0, meaning full water stress and no growth, and 1, indicating no water stress and full growth) is multiplied with the potential biomass growth to obtain the actual crop growth (CGRO). The calculation of this variable WATER is explained later in the water competition part.
Every day, total accumulated biomass per species is calculated as well as the weight of the individual plant organs. The newly formed biomass is partitioned over the different organs (leaves, roots, harvestable parts) depending on the development stage. This is done through a fixed function, which relates partitioning to development stage

(see parameterisation part). For the harvestable organ, the real yield is assumed to be 80% of the dry matter in the heads and pods of the sorghum and cowpea, respectively (Bindraban, pers. com; Van Heemst, 1988). In this way, account is made for the biomass in spills of the ears and shells of the seeds.
The increase in leaf area index (LAI) is determined by converting the increase in leaf dry weight to an increase in leaf area with the help of specific leaf area (SLA). The value of SLA changes slightly during development (Penning de Vries *et al.*, 1989). The green leaf area is assumed to senesce from generative stage onwards. The rate of senescence is a fixed fraction of the green leaf area.

Plant height and rooting depth

Plant height (HEIGH) is related to development stage, which is derived from a fixed function (Penning de Vries *et al.*, 1989). With this method, the plant height is not depending on the above ground biomass.
The rooting depth (RD) is assumed to be proportional to the plant height and thus indirectly depending on development stage. Maximum rooting depth (RDMAX), maximum plant height (HMAX) and plant height are needed to calculate the rooting depth (Shanholtz and Younos, 1994; equation 3.8a, b).

RD11=HEIGH1*RDMAX1/HMAX1 equation 3.8a
RD1=MIN(RD11,RDMAX1) equation 3.8b

Other particulars

Cowpea finishes its development earlier than sorghum (because of the lower temperature sum needed for full development). When cowpea development is completed, the plant stops accumulating biomass and doesn't transpire any more but stays on the field acting as a kind of mulch, thus decreasing evaporation.

Competition for water

Soil system

Considered is the soil profile which is potentially used for rooting (RDMAX of the deepest rooting species). This soil profile is divided into four layers. Their thickness at each moment is determined by the current rooting depth of the plant species, the depth from which water for evaporation is extracted from the soil and the maximum rooting depth of the deepest rooting species. The minimum of these four depths makes up the first layer, the second layer is determined by the difference between the shallowest and shallowest but one, etcetera (Figure 3.1). The fourth layer is a layer without roots and doesn't exist any more when the maximum rooting depth of the deepest rooting species is reached. The calculation of the layer thickness is done in subroutine LAYER. Per layer, the amount of water (WA) is given in millimetres and it is assumed that this water is evenly distributed over the layer.
A subroutine (DIST) determines the relative division of the rooting depth over the first three layers. This is also done for the evaporation.

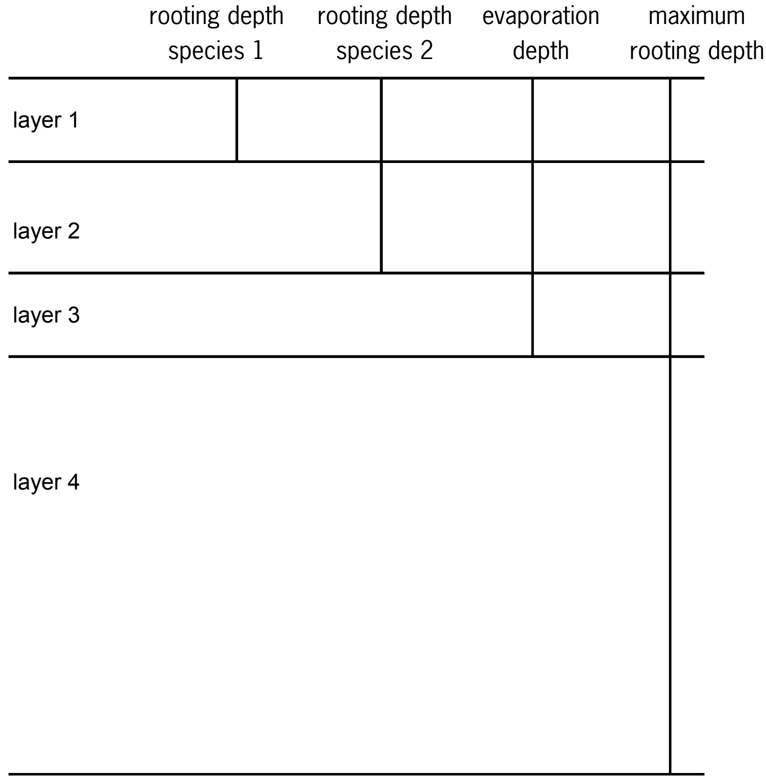

Figure 3.1. Schematic overview of a possible rooting situation in the soil.

Growth of the layers

The thickness of the layers changes over time due to increasing rooting depths. The average increase in rooting depth per time step is calculated. The amount of water which becomes newly available (W_{extra}) is proportional to the increase of rooting depth (ΔRD) divided by the thickness of the layer into which the roots grow (equation 3.9).

$$W_{extra}=WA^{*}\ \Delta RD/Layer \qquad \text{equation 3.9}$$

If the increase in rooting depth is such that the roots grow through a layer into the next, the total amount of water available in the entire former layer becomes available to the plant. Calculations of water becoming available through root growth are done in the subroutines EXTRA1, EXTRA2 and EXTRA3 for the growth of the layers 1, 2 and 3, respectively. The output from these subroutines is worked out as the total extra water which becomes available for layer 1, 2 and 3.

Soil properties

The important soil properties are the water content at which an equilibrium in soil water content exists after saturation (field capacity, FC), the water content below which it is not possible anymore for the plants to extract water from the soil (wilting point, WP) and the water content when the soil is completely dried by the air (air dry, AD). Water between the actual water content and wilting point was in principle available for the plants, whereas water between the actual water content and air dry was available for evaporation. Percolation to lower levels occurs when the actual water content becomes higher than field capacity. When this happens, water between the actual water content and field capacity percolates to the layer below. The calculations are done in subroutine PERL1 (layer 1) and PERL2 (other layers).

Available water

Per layer, the amount of water available to the plants (AVAIW1) is calculated from the actual amount of water (WA) and the wilting point (WP). The water available for evaporation (AVW1T) is divided into two parts: the first part is the same as the plant available water (AVAIW1) and the second part is only available for evaporation (water between wilting point and air dry) (AVAV1). Water which is added to the system through rain is already incorporated in this available water. All rain is assumed to reach the soil.

Potential evapotranspiration, transpiration and evaporation

The potential evaporation and transpiration are calculated with the Penman-formula in the subroutine PENMAN. This is done in an adapted subroutine taken from the LINTUL2 model (Schaapendonk and Spitters, 1990). Potential evapotranspiration is depending on radiation, temperature, wind speed and vapour pressure deficit. Evapotranspiration is driven by the radiation to vaporise water and by air drying power to remove the vapour. Potential transpiration (TRAPOT in the main model, PTRAN in the subroutine) is determined by the total leaf area index in a negative exponential function (equation 3.10).

PTRAN = (1.-EXP(-LAI)) * (PENMRC + PENMD) / LHVAP equation 3.10

PENMRS and PENMRC are the radiation vaporisation terms for soil and crop, respectively and PENMD is the air drying power term, which is the same for both crop and soil. LHVAP is the latent heat needed for evaporation. The potential evaporation (EVAPOT in the model, PEVAP in the subroutine) also depends on the total LAI (equation 3.11).

PEVAP = EXP(-LAI) * (PENMRS + PENMD) / LHVAP equation 3.11

The original subroutine gives a factor 0.5 to be multiplied with the total LAI in the exponential function. Xie *et al.* (2001) give the same formula without the factor 0.5 for calculations of sorghum and maize. This is also done in this model (see Appendix III for further explanation).
The potential transpiration in turn is divided over the plants by their share in intercepted radiation (Kropff and Van Laar, 1993; equation 3.12a, b: TRPOT1 and TRPOT2 are the potential transpiration for sorghum and cowpea, respectively).

TRPOT1=IINT1/(IINT1+IINT2)*TRAPOT equation 3.12a
TRPOT2=IINT2/(IINT1+IINT2)*TRAPOT equation 3.12b

Calculation of water uptake per layer: actual transpiration and evaporation

Transpiration is not always potential, but is sometimes reduced depending on the fraction soil water and the critical water content. The critical water content depends on the type of photosynthesis (C_3 or C_4) and on soil type, and is higher for C_3 than for C_4 plants (Penning de Vries *et al.*, 1989; Kropff and Van Laar, 1993). Water below wilting point is not available to the plant. From wilting point to the critical water content, the fraction water which is available increases linearly from zero to one. Above the critical water content, all water is available to the plants. Evaporation reduction depends on the water content of the upper soil layer (layer 1) (Kropff and Van Laar, 1993; see Figure 3.2). In the model, the competition for water is assumed to be indirect. Plant roots are not competing for water, but water used at a certain day is not available any more the next day.
The calculations for actual transpiration and evaporation from layer 1 are shown as an example.

First, the potential amount of water which can be taken up by the plant species in layer 1 is calculated (ASP1L1 and ASP2L1 for sorghum and cowpea, respectively). The function for the reduction in transpiration by soil water content is hereby taken as a measure for the reduction in potential available water (see also parameterisation part). Also the amount of water available for evaporation is calculated (AEVAL1) (equations 3.131-c).

ASP1L1=AFGEN(CRIT1,WA11/(LAYER1*1000.))*WA11*INSW(FRRD11-0.001,0.,1.) equation 3.13a
ASP2L1=AFGEN(CRIT2,WA11/(LAYER1*1000.))*WA11*INSW(FRRD21-0.001,0.,1.) equation 3.13b
AEVAL1=AFGEN(EVAP,WA11/(LAYER1*1000.))*WA11*INSW(FREVA1-0.001,0.,1.) equation 3.13c

ASP1L1 stands for the Available water to SPecies 1 in Layer 1. ASP2L1 is the Available water for SPecies 2 in Layer 1 and AEVAL1 is the Available water for EVAporation in Layer 1. The first term in each calculation is the function for determining the difficulty of water uptake by the plants or the reduction in evaporation due to low soil water content. The water content in millimetres is converted to a fraction based on the thickness of the soil layer. The second term is the amount of soil water and the third term is a function which determines if the plant species was present in the relevant layer (FRRD11, FRRD21 and FREVA1 are output from the subroutine DIST). If less than 0.1% of the roots or the evaporation depth is present in a certain layer, this is neglected in that layer. This calculation is done for every layer.

Second, the fraction of potential available water in each layer in the total potential available water of a species is calculated. For species 1, the example is given in equation 3.14a-c.

FSP1L1=ASP1L1/NOTNUL(ASP1L1+ASP1L2+ASP1L3) equation 3.14a
FSP1L2=ASP1L2/NOTNUL(ASP1L1+ASP1L2+ASP1L3) equation 3.14b
FSP1L3=ASP1L3/NOTNUL(ASP1L1+ASP1L2+ASP1L3) equation 3.14c

FSP1L1 stands for the Fraction of total water of SPecies 1 which can be taken from Layer 1.

In the third step, the potential transpiration/evaporation is divided over the layers by multiplying the total potential transpiration times the fraction of potential available water in that layer and the reduction in transpiration or evaporation through low soil water content (equation 3.15a-c).

S1POT1=TRPOT1*FSP1L1*AFGEN(CRIT1,WA11/(LAYER1*1000.)) equation 3.15a
S2POT1=TRPOT2*FSP2L1*AFGEN(CRIT2,WA11/(LAYER1*1000.))*...
INSW(DEV2-2.099,1.,0.) equation 3.15b
EVAPL1=EVAPOT*FEVL1*AFGEN(EVAP,WA11/(LAYER1*1000.)) equation 3.15c

S1POT1 is the POTential transpiration from layer 1 for Species 1. EVAPL1 is the Potential EVAporation from Layer 1. The fourth term in the calculation of the second species (cowpea) is to make sure that there is no transpiration anymore when the second crop has reached full development.

Then, the total amount of water which is asked from the amount of soil water, TOTL1P, is calculated. TOTL1P is calculated as the potential transpiration of crops 1 (S1POT1) and 2 (S2POT1) and the potential evaporation (EVAPL1). TOTL1P is compared to the potential amount of useable soil water (all the water above air dry point, AVW1T). If the ratio AVW1T/TOTL1P is less than 1, so if more water is demanded than is available, the S1POT1, S2POT1 and EVAPL1 are reduced by this ratio (equation 3.16a-e).

TOTL1P=S1POT1+S2POT1+EVAPL1 equation 3.16a
FR1=MIN(1.,AVW1T/NOTNUL(TOTL1P)) equation 3.16b
TRAN11=S1POT1*FR1 equation 3.16c
TRAN21=S2POT1*FR1 equation 3.16d
EVAL1=EVAPL1*FR1 equation 3.16e

TRAN11 and TRAN21 are the actual transpiration taken from layer 1 (second suffix) by plant species 1 and 2, respectively (first suffix). EVAL1 is the actual amount of water used for evaporation from layer 1.
This calculation is done for every layer. Then, the transpiration from each layer per plant species is added to calculate the total transpiration for each species, resulting in TRANS1 for sorghum and TRANS2 for cowpea. This is also done for evaporation (EVA). The growth reduction for the plants is depending on variable WATER, which is the

ratio actual/potential transpiration (Kropff and Van Laar, 1993; Van Noordwijk and Lusiana, 1999). This variable is multiplied with the potential growth rate (GROPO).
Per layer, also the total uptake of water for transpiration is calculated by adding the transpiration of the two plant species.

Percolation

Apart from water loss through evaporation and transpiration, water is also removed from the soil layers by percolation. At the end of the day the change in the amount of soil water (through rain, root growth, evaporation and transpiration) is calculated. If the water content at would become higher than field capacity, the amount of water which is above field capacity percolates to the next lower layer. If water percolates from the lowest layer, it is lost from the system and not available for crop growth any more. The calculations are done in the subroutines PERC1 for layer 1 and PERC2 for the other layers.

3.2 Parameterisation

Parameters were obtained from various sources, mainly literature. Two often used sources are a literature overview of parameters for simulations of a large number of crops (Van Heemst, 1988) and a book by Penning de Vries *et al.* (1989) on simulation of ecophysiological processes in several crops, among which are the two crops used in the presented study.

Soil characteristics

The crops are assumed to grow on a loamy soil (Tefera and Tana, 2002; Gilbert *et al.*, 2003; Craufurd, 2000). The characteristics of the soil are shown in Table 3.1 and are taken from Penning de Vries *et al.* (1989). The water content of the soil was 15% at the start of the simulation. Water for evaporation is taken from the first 30 cm of the soil (Shanholtz and Younos, 1994; Jalota *et al.*, 2000).

Table 3.1. Soil characteristics for a loamy soil.

name	description	fraction soil water
FC	field capacity	0.36
WP	wilting point	0.11
AD	air dry	0.01

The functions to express the reduction in the potential transpiration of C_4 and C_3 crops were derived from Kropff and Van Laar (1993). The critical water content θ_{cr} below which transpiration is hampered for a plant species was calculated with equation 3.17, where θ_{wp} is the water content at wilting point and θ_{fc} is the water content at field capacity.

$$\theta_{cr} = \theta_{wp} + (1-p)(\theta_{fc} - \theta_{wp}) \qquad \text{equation 3.17}$$

The p-value depends on the evapotranspiration demand each day, but was kept constant at an average of 0.5 for C_3 and 0.7 for C_4 species, resulting in the critical water content of 0.185 for sorghum and 0.235 for cowpea.
The function for the reduction in evaporation due to dry soil was taken from Kropff and Van Laar (1993) (Figure 3.2).

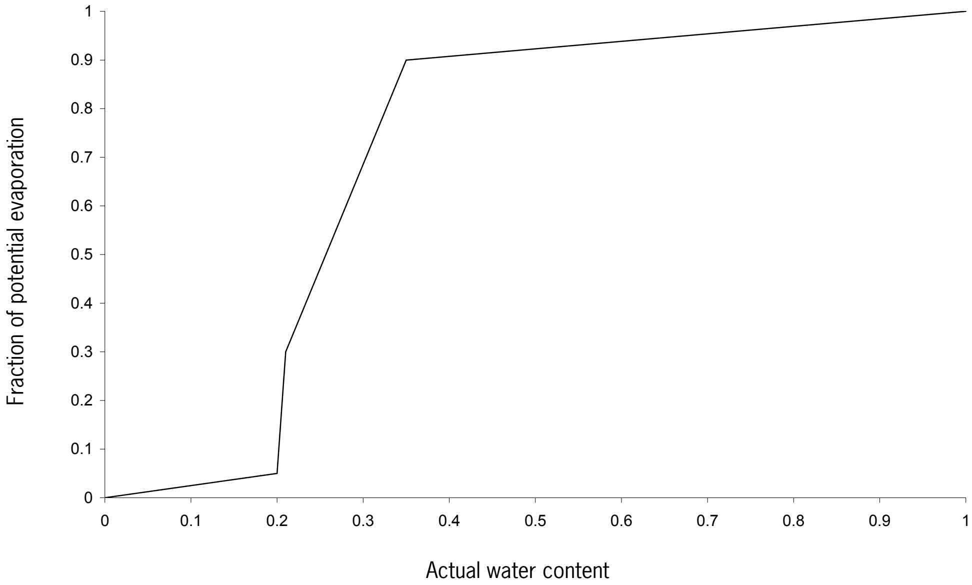

Figure 3.2. The fraction water which can actually be transpired as a function of the actual water content of the soil (source: Kropff and Van Laar, 1993).

Plant properties

The names, descriptions and values of the plant initial conditions and parameters are given in Table 3.2 and 3.3, respectively. Where needed, an explanation is given for the choice of a value. Initial values of development and temperature sum were zero.

Table 3.2. Initial values for plant growth of sorghum and cowpea, respectively.

category	name	explanation	sorghum	cowpea	units
initial statements	IBIOM	initial biomass	0.11	0.09	g/plant
	IHEAD/IPOD	initial harvestable organ weight	0	0	g/plant
	ILAI	initial leaf area	8.125E-04	9.375E-04	-
	ILEAF	initial leaf weight	0.056	0.055	g/plant
	IROOT	initial root weight	0.023	0.035	g/plant

All values were derived from van Heemst, with the help of partitioning over the organs and the SLA. The values are converted to g/m^2 by the density.
Table 3.3 gives the parameters for the growth of the sorghum and cowpea plants.

Table 3.3. Parameters for the growth of sorghum and cowpea as obtained from literature.

name	parameter	sorghum	cowpea	units
HMAX	maximum height	2	0.75	m
K	extinction coefficient	0.6	0.85	-
LUE	light use efficiency	2.5	1.8	g MJ^{-1} PAR
RDLEA	fraction leaf senescence	0.06	0.03	-
RDMAX	maximum rooting depth	0.6	0.4	m
SLA	specific leaf area	0.025	0.022	m^2 g^{-1}
TBASE	base temperature for development	11	8	°C
TMAX	maximum temperature for development	42	-	°C
TOPT	optimum temperature for development	30	-	°C
TSUM1	temperature sum till flowering	1000	600	°Cd
TSUM2	temperature sum till maturity	660	630	°Cd

The maximum crop height for both crops was taken from Penning de Vries *et al.* (1989). The extinction coefficient for sorghum was taken as an average value of grains (Goudriaan, 1977, in Penning de Vries *et al.*, 1989) and is within the range 0.3-0.7, given by Van Heemst (1988). For cowpea, 0.85 was used, to represent a plant with more horizontal leaves.
Light use efficiencies were estimated from values found in literature. For sorghum, Huda (1987) used 3 g/MJ PAR as a reasonable value for LUE and he reported literature values of 1.2-2.82 g/MJ PAR. Hammer and Muchow (1994) used a value of 2.5 g/MJ PAR, while Gilbert *et al.* (2003) found 2.41 g/MJ PAR for sorghum in an intercrop with cowpea. Based on these findings, a value of 2.5 g/MJ PAR was chosen.
Literature values of cowpea radiation use efficiency varied enormously. The results of Idinoba *et al.* (2002) from cowpea pure stand experiments gave a radiation use efficiency of 2.95 g/MJ PAR. Muchow *et al.* (1993) obtained a radiation use efficiency of 2.05 g/MJ PAR. In his literature study, Muchow *et al.* (1993) reported values of 0.8-1.01 g/MJ solar radiation for cowpea. C_4 plants like sorghum have higher radiation use efficiency than C_3 plants (Idinoba *et al.*, 2002). Further, the chemical composition of the grain and legumes differ; it takes more energy to compose proteins from legumes than the starch from the grains. Therefore, the value used in the model was 1.8 g/MJ PAR, lower than sorghum and within the range found in literature.
The fraction leaf senescence per day was estimated at 0.06 for sorghum and 0.03 for cowpea. Cowpea had lower leaf senescence due to easier access to nitrogen and therefore less need to abandon old leaves to reallocate nitrogen (symbioses with rhyzobium bacteria).
The maximum rooting depth was 0.6 and 0.4 m for sorghum and cowpea, respectively, based on personal observations of Van Ast (pers. comm.). Literature gave higher values, 1.4 and 1.0 m by Penning de Vries *et al.* (1989) and 1.5 and 1.2 m by Van Heemst (1988), but dry soils often give much mechanical resistance which prevents deep penetration of the soil by the roots.
The specific leaf area was taken from Penning de Vries *et al.* (1989). A function was used which allows variation of the SLA during the different development stages (Figure 3.3).
The base temperature for cowpea was taken from Van Heemst (1988). For sorghum, a more elaborate function was used with an optimum temperature TOPT and maximum temperature TMAX, taken from Hammer *et al.* (1993).
The temperature sums for vegetative (TSUM1(1-2)) and generative development (TSUM2(1-2)) were taken from Van Heemst (1988). This source gave various values for some temperature sums. For sorghum, the intermediate value for TSUM11 was taken. For TSUM12, only one value was given. For cowpea, TSUM21 for photoperiod-insensitive genotypes was taken and for TSUM22 the most recent value.

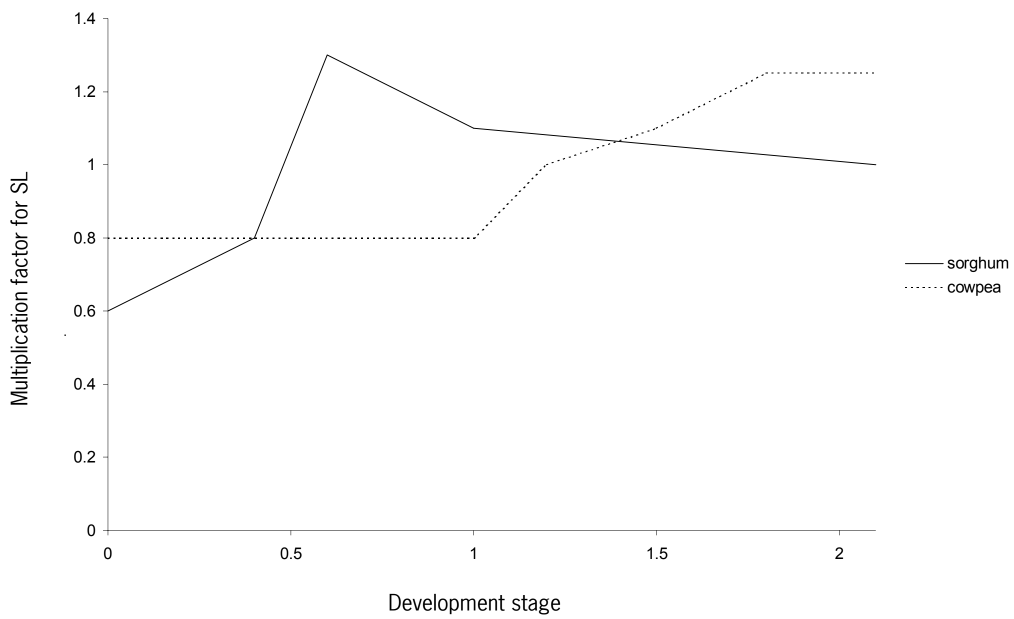

Figure 3.3. The multiplication factor for the specific leaf area (SLA) depending on development stage (source: Penning de Vries et al., 1989).

The partitioning of the dry weight over the organs is given in Figure 3.4 (sorghum) and Figure 3.5 (cowpea) and was derived from Van Heemst (1988).

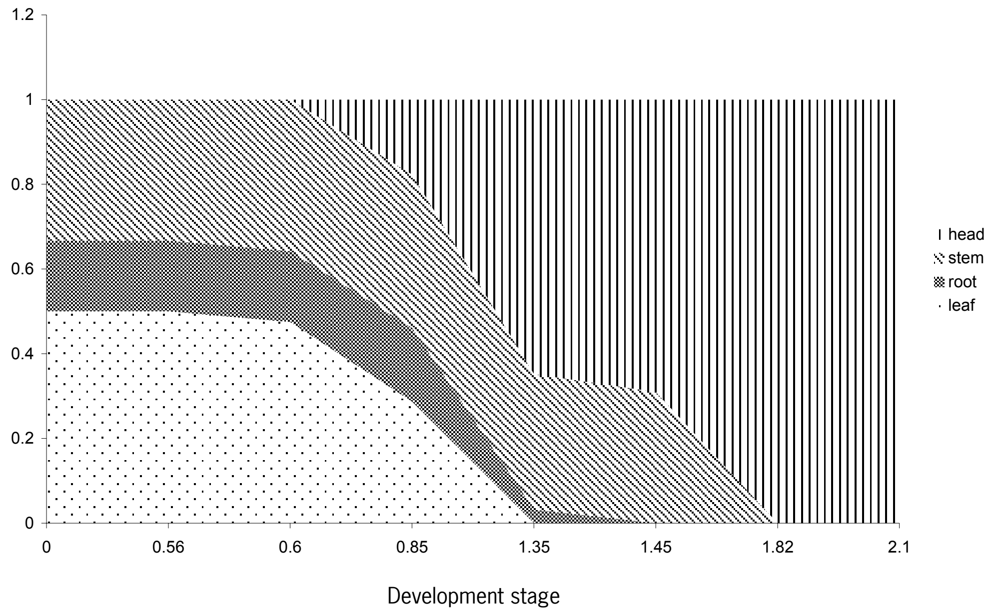

Figure 3.4. *The distribution of the newly accumulated dry weight over the organs as a function of development stage (derived from Van Heemst, 1988).*

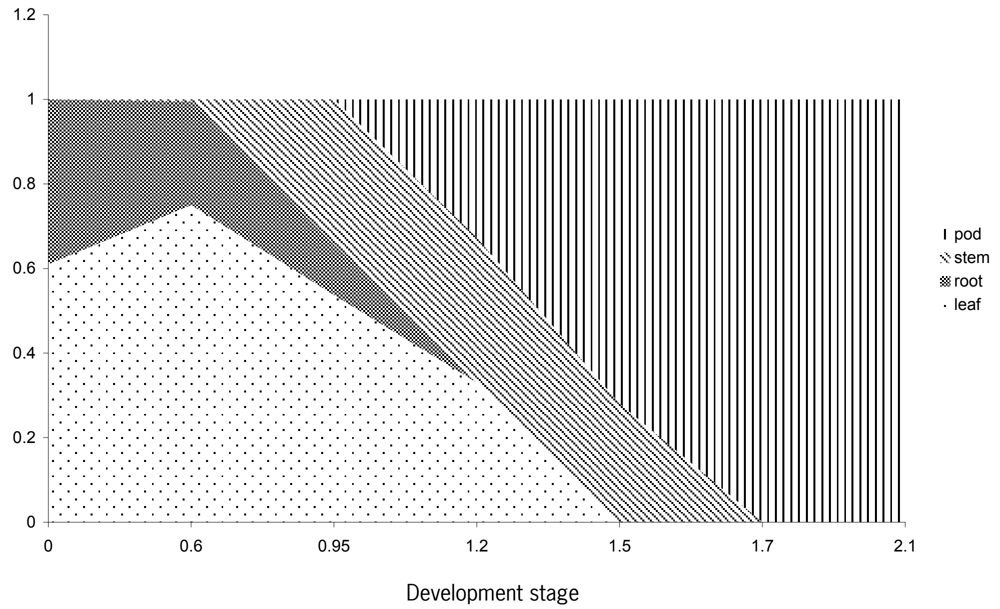

Figure 3.5. *The distribution of the newly accumulated dry matter over the organs in cowpea as a function of development stage (derived from Van Heemst, 1988).*

Plant height depended on development stage according to Figure 3.6 (Penning de Vries *et al.*, 1989).

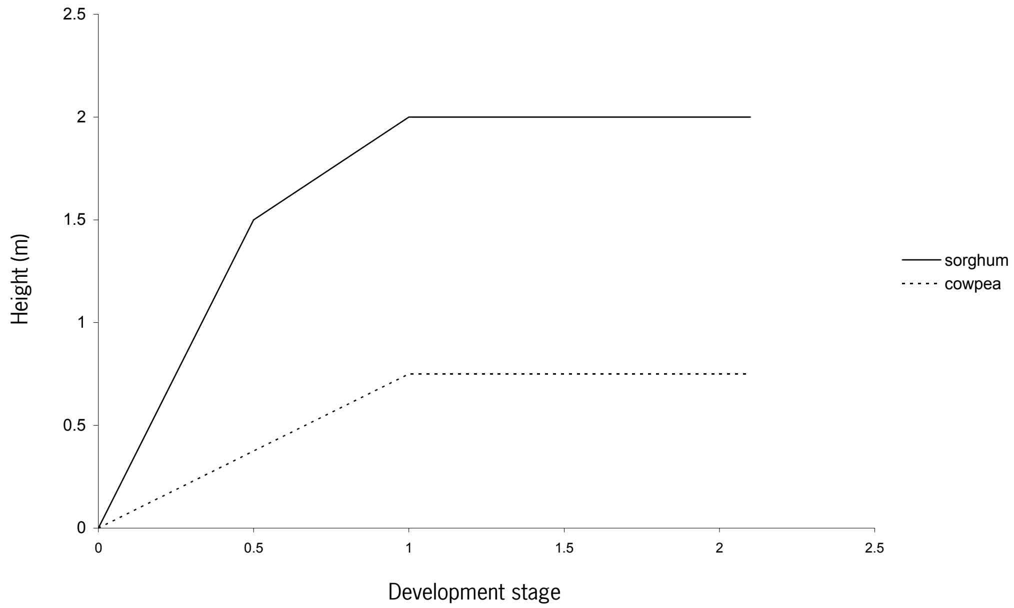

Figure 3.6. The height of sorghum and cowpea, depending on their development stage (source: Penning de Vries et al., 1989).

Densities

The densities reported in literature cover a wide range for the intercropping and the pure stands of the species used. Faris *et al.* (1983) used a density of 25 plants/m^2 for the sorghum in pure stand and 12.5 plants/m^2 in intercropping. For cowpea, they used a density of 3.1 plants/m^2 in intercrop and 6.3 plants/m^2 in monoculture. Rees (1986a,b) used different densities for sorghum: wide, 1.3 plants/m^2; standard 5.3 and 10.7 plants/m^2 and narrow, 21.3 plants/m^2. His cowpea densities were 7 plants/m^2 in low density intercrop, 27 plants/m^2 in standard density intercrop and 53 plants/m^2 in high density intercrop and monoculture. Idinoba *et al.* (2002) used 6.6 plants/m^2 for cowpeas in monoculture. Muchow *et al.* (1993) used 18 and 35 plants/m^2 for cowpeas in monoculture. Craufurd (2000) used densities of 1.1-6.0 plants/m^2 for sorghum in intercropping with cowpea and 0.7-3.8 plants/m^2 for cowpea. Gilbert *et al.* (2003) used 5 plants/m^2 of sorghum and 2.5 or 5 plants/m^2 of cowpea. In all the experiments, the inter- and intrarow distances varied.
Since the densities in literature varied so widely, densities for the model were chosen which made analysis and interpretation of the simulation results easier. For pure stands, densities of 4 and 8 plants/m^2 for sorghum and 8 and 16 plants/m^2 for cowpea were used. Cowpea plants are smaller than sorghum plants, so their density could be higher. The densities are within the range found in literature. Intercropping densities were combinations of these densities: high density sorghum with high density cowpea, high density sorghum with low density cowpea and low density sorghum with low density cowpea. For further explanation, see the 3.3.

Weather data

The model starts at emergence of the crops, which was set at day 185 (July 4) (close to the planting date of Gilbert *et al.* (2003)), which assured optimal growing conditions. To run the model, weather data from Mali of the year 1950 were used. Figure 3.7 presents the average daily temperatures and the PAR-radiation and Figure 3.8 the rainfall pattern throughout the growth of the crops.

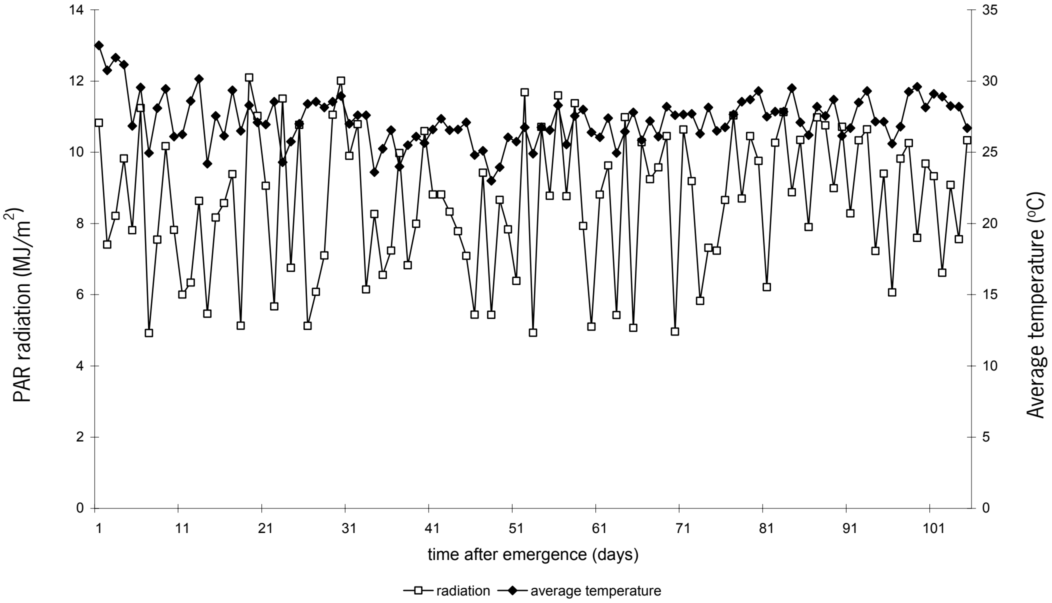

Figure 3.7. *The course of average temperature and PAR-radiation during the growth of the crops, based on weather data from Mali in 1950.*

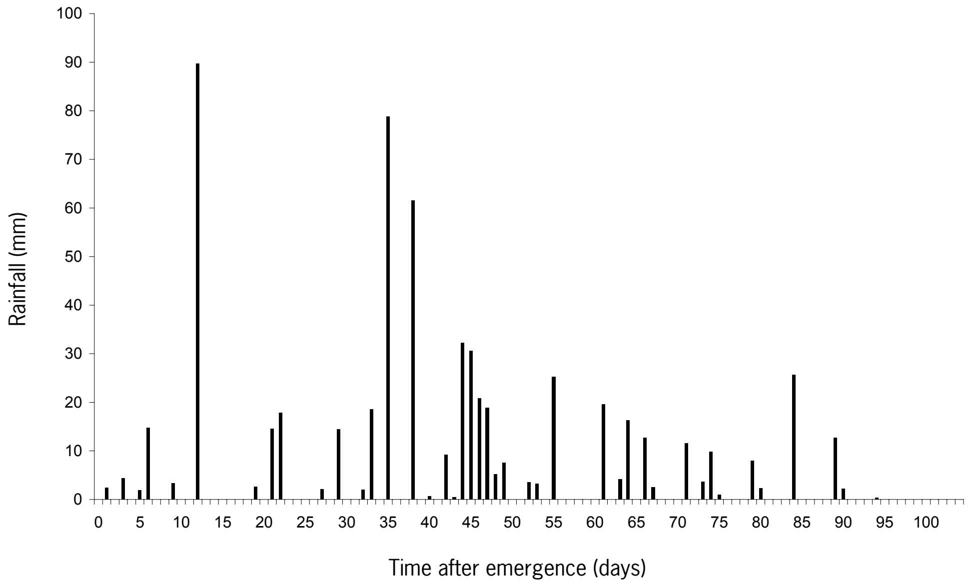

Figure 3.8. *The distribution and amount of rainfall over the growing season, based on weather data from Mali in 1950.*

3.3 Overview and presentation of the simulation studies

Simulations

The model was build to observe the effect of different levels of water supply on intercropping performance. Before intercropping simulations were made, the behaviour of the component crops of the intercrop was studied at two densities in pure stands to study the impact of increasing density and to act as a reference for comparisons with the intercrops.

The following simulations were performed for this goal:

- Sorghum monoculture with 4 plants/m^2 (S4)
- Sorghum monoculture with 8 plants/m^2 (S8)
- Cowpea monoculture with 8 plants/m^2 (C8)
- Cowpea monoculture with 16 plants/m^2 (C16)

The following intercrop simulations were made:

- Additive intercropping at high densities with sorghum at 8 plants/m^2 and cowpea at 16 plants/m^2 (S8C16)
- Additive intercropping at low densities with sorghum at 4 plants/m^2 and cowpea at 8 plants/m^2 (S4C8)
- Intermediate intercropping, sorghum at high density and cowpea at low density (S8C8)

These are a high intercrop density (S8C16) and a low intercrop density (S4C8), with the same ratio between sorghum and cowpea. The intercrop S8C8 represents a full crop of sorghum with some cowpea as ground cover, which is a common practice (Morris and Garrity, 1993a). The combination S4C16 was not made, because a main crop of cowpea with some sorghum for extra yield hardly occurs (Gilbert, 1996).

The aim of the simulations was to find out whether resource input level, in this case water, affects the yield advantage of an intercropping system. When modern agricultural practices, like irrigation, would be used to increase the input level, how would this affect the uptake, use efficiency and productivity of the intercrops. Therefore, all simulations were done at four different levels of water supply to study the effect of different amounts of water input. Full rainfall for the pure stand simulations was 619 mm for sorghum and 554 mm for cowpea. In addition, rainfall was lowered to 75, 50 and 25% of the full rainfall. The high density of each pure stand was run with these amounts of water supply. All intercrops were also simulated with these levels of water input (amounts of water supply were the same as for the pure stands of sorghum).
All simulations started with 90 mm of soil water, evenly distributed over the top 60 cm of the soil (fraction soil water θ: 0.15).

Since the aim of the project was also to see how productivity could be improved, realistic possibilities in change of plant properties were tested. Also agronomic improvements, like change of planting time, were considered as an option.
The following plant properties were changed:

- The height of the sorghum: decreasing the height to 1.5 meter
- The LUE of cowpea: increasing to 2.0 MJ/m^2 (see values mentioned in parameterisation part)

The agronomic improvements for which the effect on productivity was examined were:

- The time of emergence: cowpea emerged one week earlier than sorghum in these scenarios; this allowed a better competitive position for the cowpea. In this scenario, the sorghum emerged one week later than normal, on day 192.
- Increasing the density: as seen in the previous chapter, there might be still opportunity for increasing the density. What happens if intercrops like S16C32 and S24C32 would be grown?
- Timing and amount of water supply: rainfall was irregular and the amounts varied widely. In this simulation, the amount of rainfall was evenly distributed over time: every day the same small amount of water was provided.

The changes had sometimes implications for the simulation model. Rooting depth depended on plant height. As the height of sorghum was changed, this would mean that the growth of rooting depth would also change. To overcome this, a function was made for the rooting depth of sorghum, which ensured the same root growth as in the original simulations.
In the simulations where the emergence time of the crops was changed, simulations of the intercrops and the pure stand of cowpea started at day 185, while the pure stand of sorghum started at day 192.
All simulations were done at the described levels of rainfall.

Definitions

As the model focuses on water use and water use efficiency, the exact definitions of these are important to know (Bessembinder *et al.*, 2005).
All the results of the simulations give the dry weight of the biomass. For the grains, this means that the normal moisture content of 12 and 14% for sorghum and cowpea, respectively (Morris *et al.*, 1990), was not included. The harvest indices were calculated as harvestable organ over total dry matter (above and below ground).
In this model situation, the water use was measured from emergence to maturity. In reality the water use might be higher, due to evaporation between sowing or land preparation and emergence and evaporation and transpiration between maturity and harvest (Bessembinder *et al.*, 2005). When the water use efficiency was regarded (WUE), this was taken as the total biomass (g/m^2) divided by the weight of water (in g/m^2) used by transpiration and evaporation. However, as the yield of the harvestable organ is equally important, water use efficiency was also calculated as the harvestable yield divided by the total water use in the period from emergence to maturity.
Finally, the Land Equivalent Ratio (LER) was calculated according to equation 2.1, relative to the same pure stand densities. This means that the LER of S8C16 was calculated as

$$LER = \frac{Y_{S8,\text{int}\,ercrop}}{Y_{S8\,pures\tan d}} + \frac{Y_{C16,\text{int}\,ercrop}}{Y_{C16,\,pures\tan d}} \qquad \text{equation 3.18}$$

In the pure stand, doubling the density can be considered as an additive intercropping of two sorghum crops at low density. Therefore, a land equivalent ratio could be calculated for the high density. The harvest obtained by each of the 'component' crops of the intercrop was half the harvest of the 'intercropping' (=high density pure stand). For obtaining the LER, the harvest of the crop in 'intercropping', which is $0.5{*}Y_{high}$, was divided by the harvest of the crop in monoculture (the low density). This ratio was also calculated for the other 'crop' and both ratios were added. This means that the LER of the high density crop is the harvest in high density divided by the harvest in low density. In formula:

$$LER = \frac{0.5 * Y_{high}}{Y_{low}} + \frac{0.5 * Y_{high}}{Y_{low}} = \frac{Y_{high}}{Y_{low}} \qquad \text{equation 3.19}$$

Presentation of the results

In each chapter first, the results at full rain are presented and secondly the results where the amount of rain was varied are given.
Elaborated results of the simulations of crops in pure stands are given (chapter 4). The development, biomass, harvestable yield and leaf growth, rooting depth, transpiration, evaporation and water use in time are shown. The amounts of water in the soil are followed in time and the destination of the rainfall is graphically illustrated (see section water balance). The water use efficiencies and LER values were calculated. The difference in water use and water use efficiency between the high and low density was calculated (equations 2.3 and 2.4, respectively).
For the intercrops (chapter 5) at full rain, the same figures are shown as for the pure stands. The water use, water use efficiencies and their difference to the pure stands were calculated and compared over the systems. Finally, the LER was calculated for the different systems.
For the simulations of the intercropping systems where the amount of rainfall was varied, only the final values of biomass and harvestable organ, total water use, water use efficiency and LER are shown in bar graphs. The differences in WU and WUE compared to the pure stands are given. If any unexpected results turned up, this was explained by analysing and presenting appropriate, more underlying processes. Graphs were made which show the ratio of productivities of intercrops and pure stands (see below, productivity).
For the simulations where variations in the plant parameters or agronomic practices were implemented (chapter 6), only final values of harvestable organ, $LER_{harvest}$ and the ratio of productivities were given. The values are compared with the original simulations and differences are explained.

The results of all simulations were, where possible, compared with literature. This was done in the part with different amounts of rain, except for crop duration.

Water balance

The inflow and outflow of water is normally given by a soil water balance. A total soil water balance is given by the following equation:

$$Soil_{initial} + \text{water supply} = Soil_{final} + \text{water loss}$$

$$Soil_{initial} + \text{Rain} + \text{Irrigation} + \text{Capillary rise} = Soil_{final} + \text{Percolation} + \text{Transpiration} + \text{Evaporation} + \text{Runoff} \qquad \text{equation 3.20}$$

In our system, capillary rise and runoff are regarded as zero. Irrigation doesn't take place. The amount of water in the soil at the start of the simulations is the same in all (inter)crops. The equation above can therefore be written to the following:

$$\text{Rain} = \Delta\text{Soil} + \text{Percolation} + \text{Transpiration} + \text{Evaporation} \qquad \text{equation 3.21}$$

ΔSoil is the change in amount of soil water. The second part of the equation is represented as bar diagrams for all simulations in the pure stands and the simulations at full rain in the intercrops. The change in soil water content can be negative in some cases. Percolation is the water which percolates through the line at 60 cm depth (maximum rooting depth of sorghum).

Productivity

To see whether the theory from chapter 2 about productivity and input is valid, graphs similar to Figure 2.2 were made for the intercropping situations. This was done for biomass, harvestable organ as well as the protein yield. For the pure stand, the density of the intercrop was doubled, but the biomass or yield was halved, to get the production from the same number of plants. In this case, the same number of plants was grown in pure stand as in the intercrop, but the crops were growing separately instead of mixed. For the protein yield, a protein content of 12% is taken for sorghum (FAO, 1995) and 25% for cowpea (www.iita.org/crop/cowpea). The latter was done, because it is not strictly correct to add grams of sorghum to grams of cowpea (whether in total biomass or harvestable organ).

4. Results and analysis of model simulations I: pure stands

In this chapter, the results of the simulations with the pure stands of sorghum growing at 4 and 8 plants/m^2 (S4 and S8) and cowpea, growing at 8 and 16 plants/m^2 (C8 and C16).

4.1 Simulation results at full rainfall

In all simulations at full rainfall, growth reduction due to water shortage occurred for any of the two crops at both densities in the first month of growth, due to low soil water content.

Crop development and growth

The development of the sorghum took 105 days (Figure 4.1), of which the vegetative development took 64 days and the generative development 40 days. This time fitted well with the values reported in literature. For example, Morris *et al.* (1990) found a development time of 105 days, Tefera and Tana (2002) had sorghum which needed 120-150 days to mature, Lightfoot and Taylor (1987) obtained a development duration of 120 days, Gilbert *et al.* (2003) observed a growing period of 101 days and Huda (1987) had experiments with sorghum which needed 80-115 days from sowing to maturity.

Cowpea took 73 days from emergence to maturity, which was in line with literature values. The vegetative and generative development phase had nearly the same duration (35 and 38 days, respectively). Rees (1986b) conducted the first harvest of indeterminate cowpea at 60-70 days. Morris *et al.* (1990) reported an average time from planting till harvest of 70 days. Cisse and Hall (?) report 70-75 days for cowpea to develop from sowing to maturity. Muchow *et al.* (1993) had periods from sowing to maturity between 67 and 71 days. Littleton *et al.* (1979) found a time from emergence to 95% of pod dry weight ranging from 61-68 days.

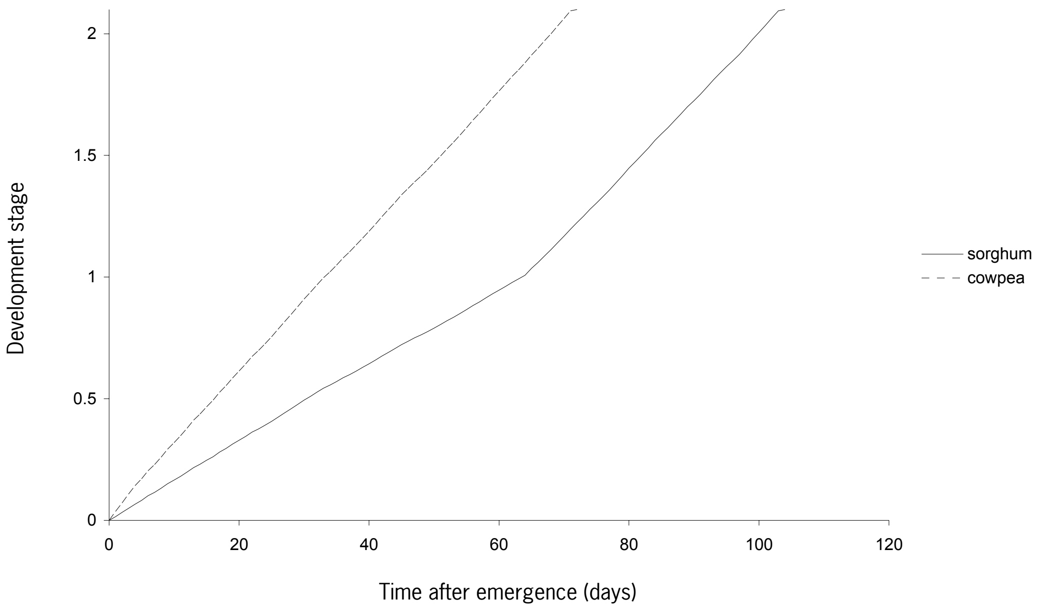

Figure 4.1. The development stage of sorghum and cowpea against time as obtained with the weather set from 1950 at Mopti, Mali.

During its development, sorghum accumulated 809 g biomass/m^2 when grown at high density and 626 g/m^2 when grown at low density (Figure 4.2). The harvestable organ of sorghum reached a weight of 290 and 232 g/m^2 at the end of the growing period for high and low density, respectively (Figure 4.3). For high and low density this corresponds to a harvest index of around 0.36. For leaf area index, a maximum value of 3.1 was obtained in high density and of 2.2 in low density (Figure 4.4).
Cowpea accumulated 361 g/m^2 in high density and 248 g/m^2 in low density (Figure 4.2). The harvestable part was 160 and 115 g/m^2 at high and low density, respectively (Figure 4.3), which resulted in a harvest indices of 0.44 and 0.46, respectively. The leaf area just covered the ground at its maximum in high density (1.1) whereas the low density didn't reach full ground cover (0.69 was the maximum LAI) (Figure 4.4).
Growth was not potential, due to low soil water content at the start of the season. Reduction in biomass was 5, 7, 20 and 24% in S8, S4, C16 and C8, respectively, compared to unlimited growth. Growth reduction was higher in the lower density of each crop due to lower ground cover and hence higher water loss by evaporation.

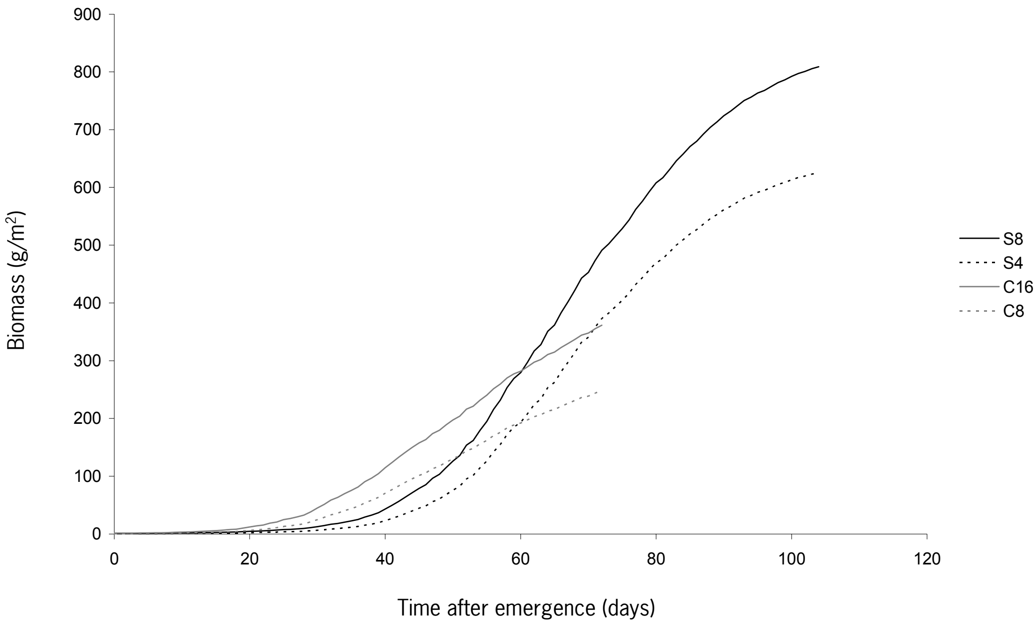

Figure 4.2. *Biomass accumulation (g/m^2) of sorghum standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.*

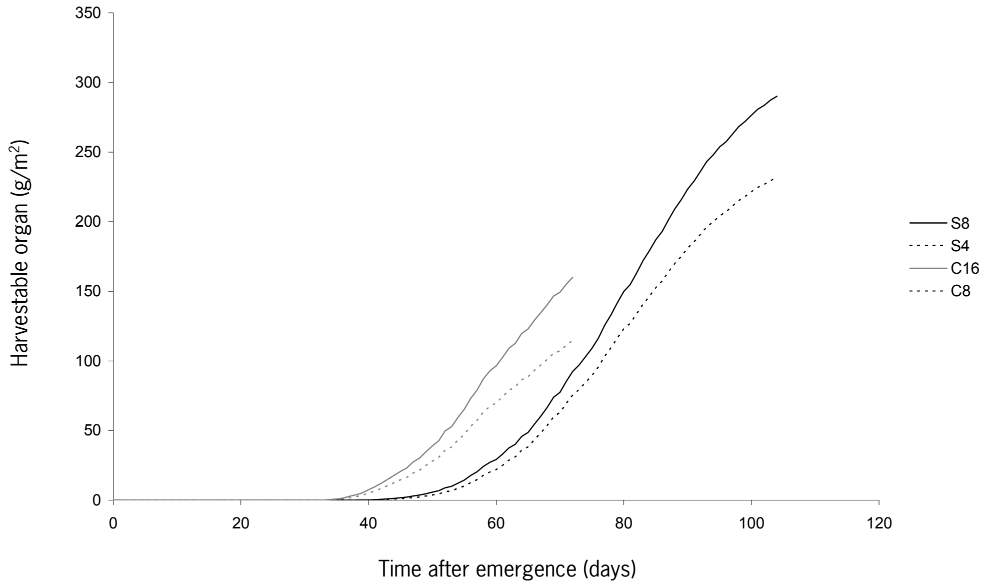

Figure 4.3. *Harvestable organ accumulation (g/m^2) of sorghum standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.*

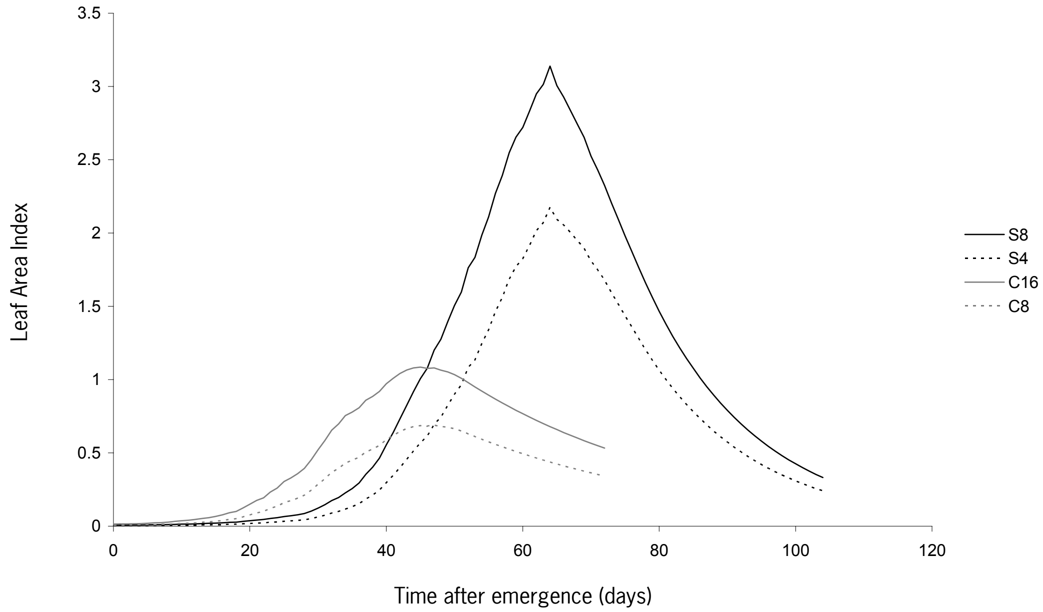

Figure 4.4. *Development of the Leaf area index of sorghum, standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.*

Maximum rooting depth was reached at 61 days after emergence (DAE) for sorghum and at 31 DAE for cowpea. Maximum rooting depth was reached just before the onset of the generative phase. The rooting depth was linked to the increase in plant height (equation 3.8a, b and Figure 3.6), which explains the faster growth of the sorghum roots in the first than in the second stage of vegetative phase (Figure 4.5). Until day 7, cowpea had a deeper rooting depth than sorghum.

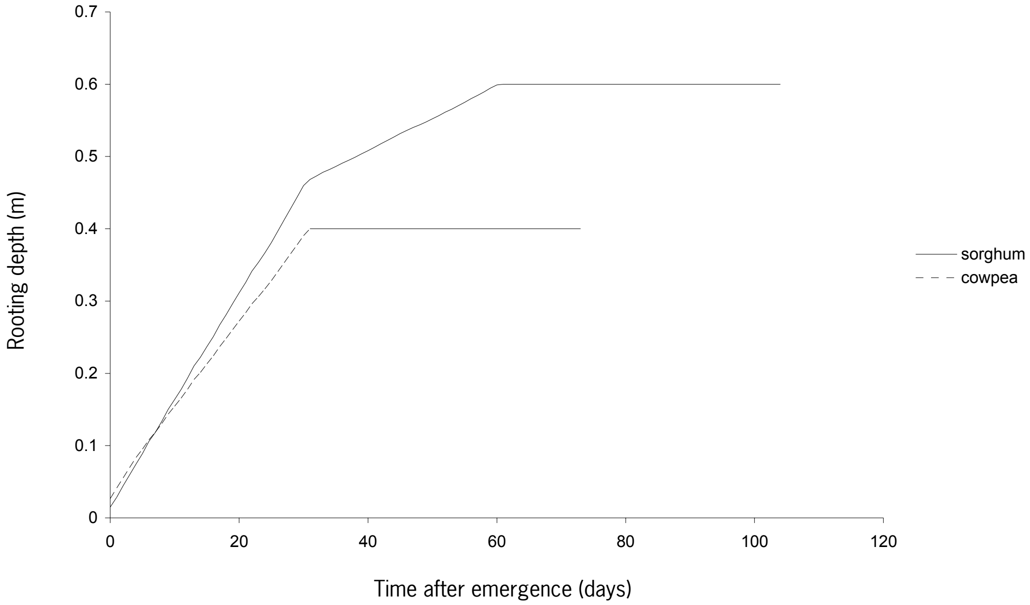

Figure 4.5. The rooting depth (m) of sorghum and cowpea through time.

Specifics of water use

For both crops, the trend in transpiration was not influenced by density, though there was always less transpiration in the low density (Figure 4.6). At maximum LAI, sorghum had a higher transpiration than cowpea, due to a higher leaf area index. The maximum in the transpiration occurred earlier for cowpea than for sorghum, due to faster leaf growth. The total transpiration of sorghum was 169 mm for high density and 137 mm for low density and 92 and 64 mm for cowpea in high and low density, respectively.

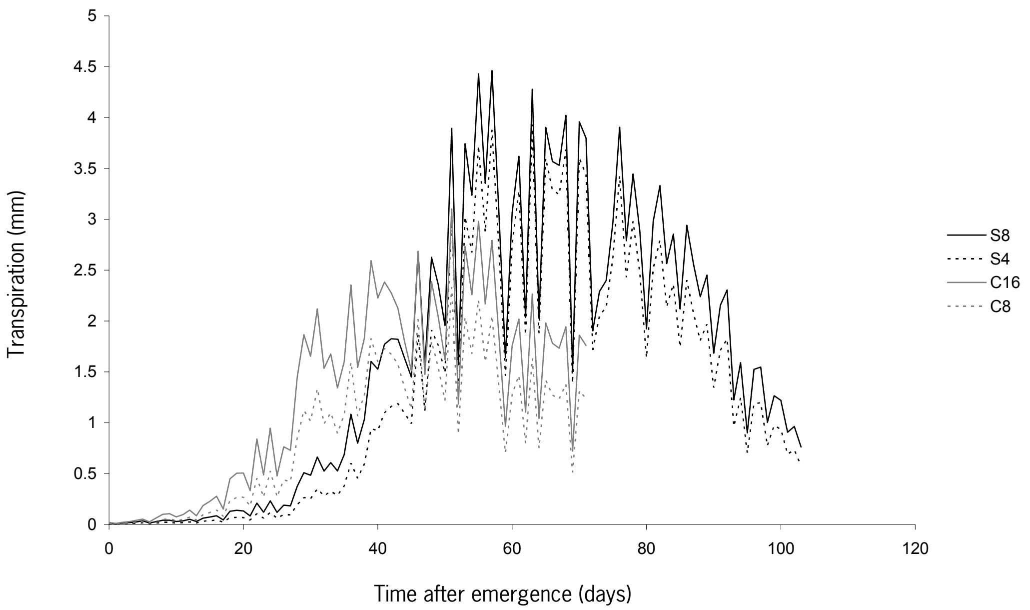

Figure 4.6. Daily transpiration (mm) of sorghum, standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.

Evaporation, the disappearance of water from the bare soil, in the first 15 days was virtually the same for sorghum and cowpea and not influence by density (Figure 4.7). Later, cowpea had a higher evaporation than sorghum and a low density stand had a higher evaporation than the high density stands of the same crop. This was due to a lower LAI. The evaporation decreased as the LAI increased (compare Figures 4.4 and 4.7). The total evaporation was 146 and 175 mm for sorghum at high and low density, respectively. For cowpea, evaporation was 116 and 143 mm at high and low density, respectively.
The daily fluctuations in the transpiration and evaporation were caused by fluctuations in the potential evaporation and potential transpiration, which in turn were caused by the temperature, radiation, wind speed and vapour pressure deficit combination for each day.

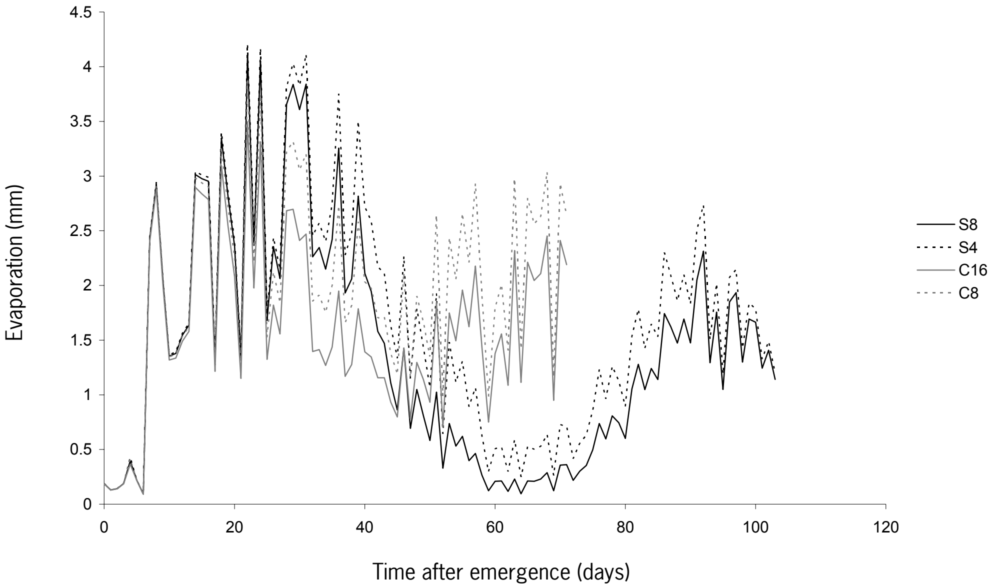

Figure 4.7. Daily evaporation (mm) of sorghum, standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.

The total water use (WU = transpiration + evaporation) was nearly the same for the low and the high density. Water use in sorghum was 314 and 313 mm for high and low density sorghum, respectively. In cowpea, the water use was 208 and 207 mm for high and low density, respectively. The water use per day had the same trend for all four simulations (Figure 4.8).
Figure 4.9 shows the destination of the water that entered as rainfall at the end of the growing season. A distinction was made between evaporation, transpiration, percolation and increase in soil water (Δ soil water). The loss of water due to percolation from the deepest layer was around 225 mm in all four cropping systems. The change in soil water was the higher in cowpea pure stands, 122 mm, than in sorghum pure stands, which added ± 80 mm to the soil water. So, while there was less rain added to the soil (due to a shorter growing period), cowpea left more water in the soil than sorghum. However, cowpea had a lower rooting depth than sorghum and hence, part of the soil water which was left after the cowpea was in the lowest 20 cm of the profile, where it was unreachable for the cowpea.

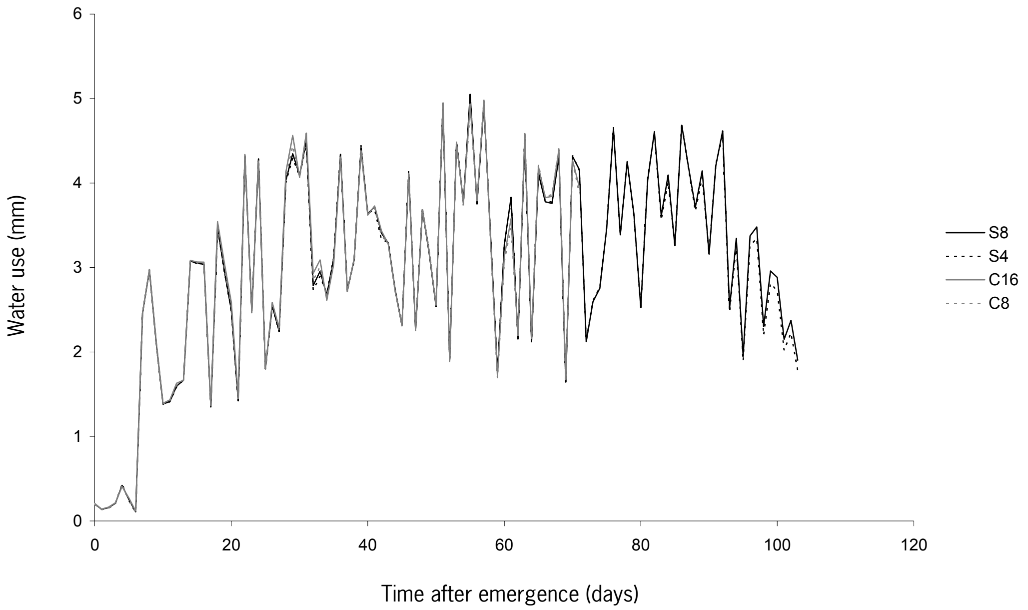

Figure 4.8. *The daily total water use of sorghum, standing at 8 and 4 plants/m² (S8 and S4) and cowpea standing at 16 and 8 plants/m² (C16 and C8) through time.*

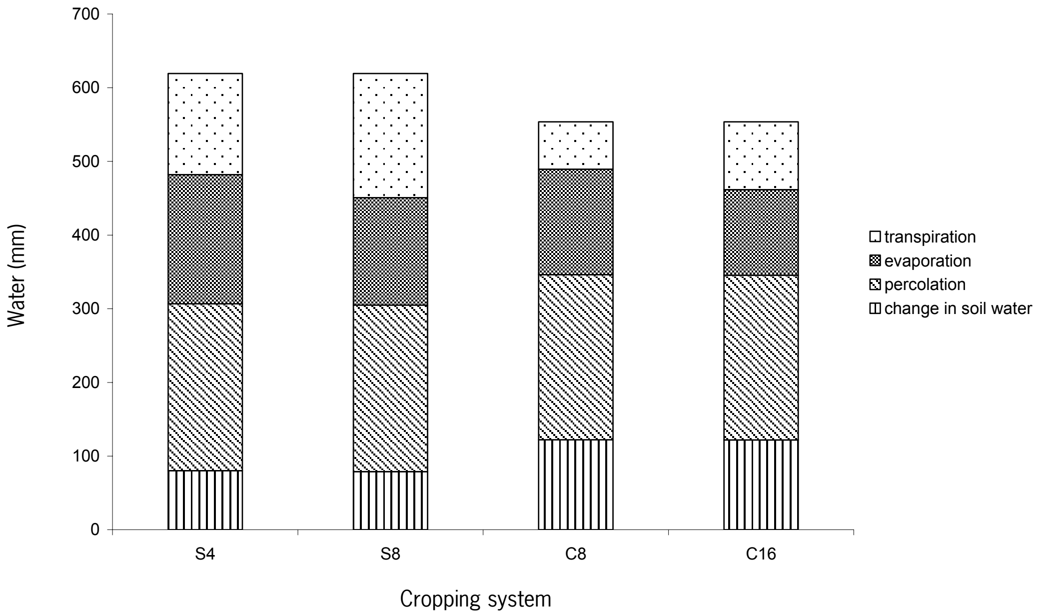

Figure 4.9. *The partitioning of the rainfall over transpiration, evaporation, percolation and change in soil water of sorghum, standing at 8 and 4 plants/m² (S8 and S4) and cowpea standing at 16 and 8 plants/m² (C16 and C8).*

The high density stands produced more biomass than the low density stands with the same water use. This resulted in lower water use efficiency (WUE, g dry matter /g water use) for the low density crops (Figure 4.10). Water was also used less efficiently in cowpea than in sorghum, due to lower ground cover and hence more evaporation. When the WUE was based on the harvestable organ, the differences in the water use efficiency were smaller, due to differences in harvest index.

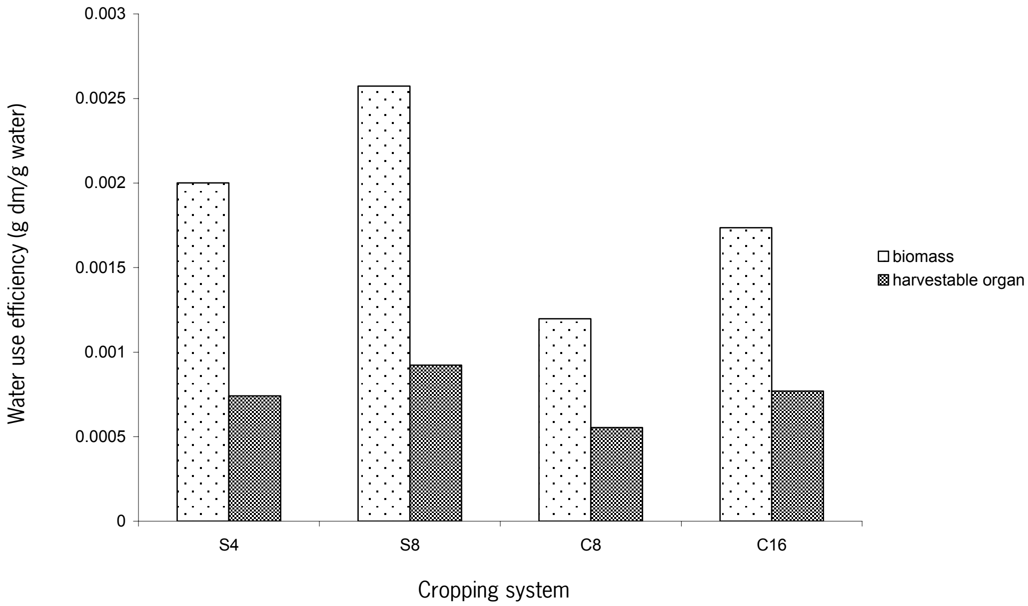

Figure 4.10. The water use efficiency for biomass and harvestable organ (both in g dm/g water) of sorghum, standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8).

Water in soil

During the main part of the growing period, water in the total soil profile (0-60 cm) increased due to rainfall and was nearly the same for all four simulations (Figure 4.11). Only in the last 15 days of sorghum growth, the amount of water in the rooted zone decreased. The peaks in the graph were caused by rainfall and the decreases by transpiration, evaporation and percolation. The amount of plant available water (paw, the amount of water in the rooted zone of the crop) increased due to growing roots and rainfall. When the maximum rooting depth was reached (day 61 for sorghum and day 31 for cowpea), there was in general a small trend of decreasing water content due to transpiration and evaporation, which was periodically compensated by rainfall. During the first 15 days the amount of water available to the plants was nearly the same for both species, but later on, sorghum had more water available for growth, due to deeper roots.

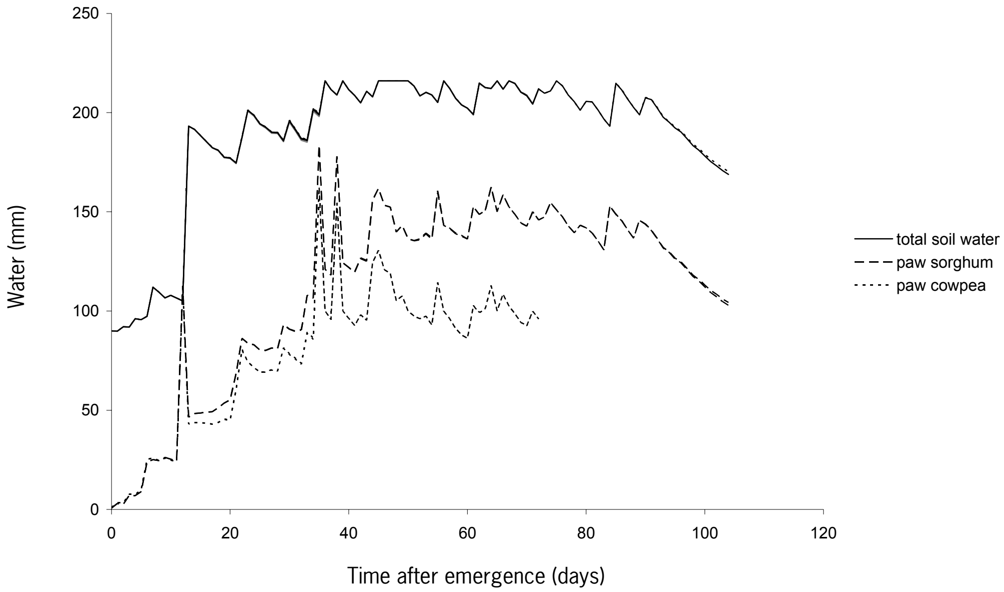

Figure 4.11. Total soil water (solid lines) and the plant available water (dashed lines) of sorghum (–) and cowpea (-..-..-) through time.

Radiation interception

The accumulation of intercepted radiation slowed down towards the end of the growing period, when the LAI was not expanding any more and even decreasing (Figure 4.12). The difference between the amounts of light intercepted by high and low density crops expanded, due to a positive feedback between light interception and leaf area production. Final values of intercepted light were 323 and 250 MJ/m^2 for sorghum at high and low density, respectively. 201 and 138 MJ/m^2 was accumulated by cowpea at high and low density, respectively. At optimal growth, the light interception would be 341, 268, 249 and 182 MJ/m^2 for S8, S4, S16 and C8, respectively.

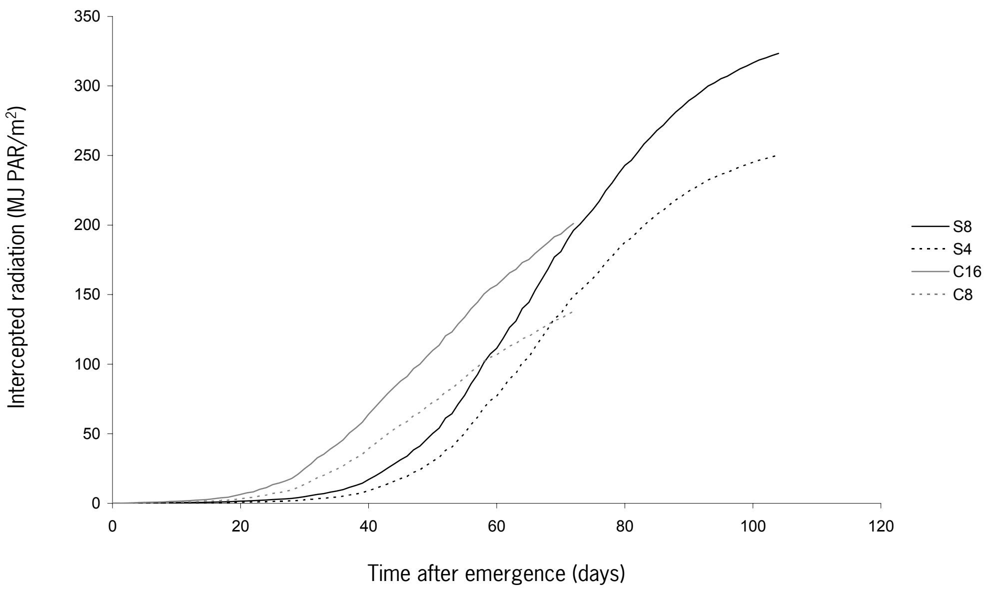

Figure 4.12. The cumulative intercepted radiation of sorghum, standing at 8 and 4 plants/m^2 (S8 and S4) and cowpea standing at 16 and 8 plants/m^2 (C16 and C8) through time.

LER, ΔWU and ΔWUE

The LER for comparing high and low density was 1.29 for sorghum and 1.46 for cowpea when biomass was considered and 1.25 and 1.40 for the harvestable organ of sorghum and cowpea, respectively. This means that under these circumstances, it was more favourable to grow the high density than the low density of either species. The LER for the harvestable organ was lower because at high density there was more competition for light in the generative phase than in the low density.
The water use in high density increased slightly compared to the low density; ΔWU (equation 2.3) is 0.5% for sorghum and 0.4% for cowpea. With nearly the same water use and with higher biomass production, the water use efficiency for biomass increased when the density was increased, ΔWUE_{biom} (equation 2.4), was 29% for sorghum and 45% for cowpea. The increase in water use efficiency for harvestable organ, ΔWUE_{harv}, was 25 and 39% for sorghum and cowpea, respectively. So, not only with respect to absolute biomass and harvestable yield, but also for water use efficiency, it was more efficient to grow a high density stand under these weather circumstances.

4.2 Simulation results at various levels of water input

In this part of the chapter, the growth and behaviour of the high density crops under the different amounts of water supply are studied.

Biomass production, harvestable organ and LAI

Below, the daily growth reduction factor during sorghum growth (Figure 4.13) and cowpea growth (Figure 4.14) in high density at different levels of water input is shown. This is the variable WATER from the model. The growth reduction was zero when the variable WATER had the value one and growth reduction was complete when variable WATER had the value zero.

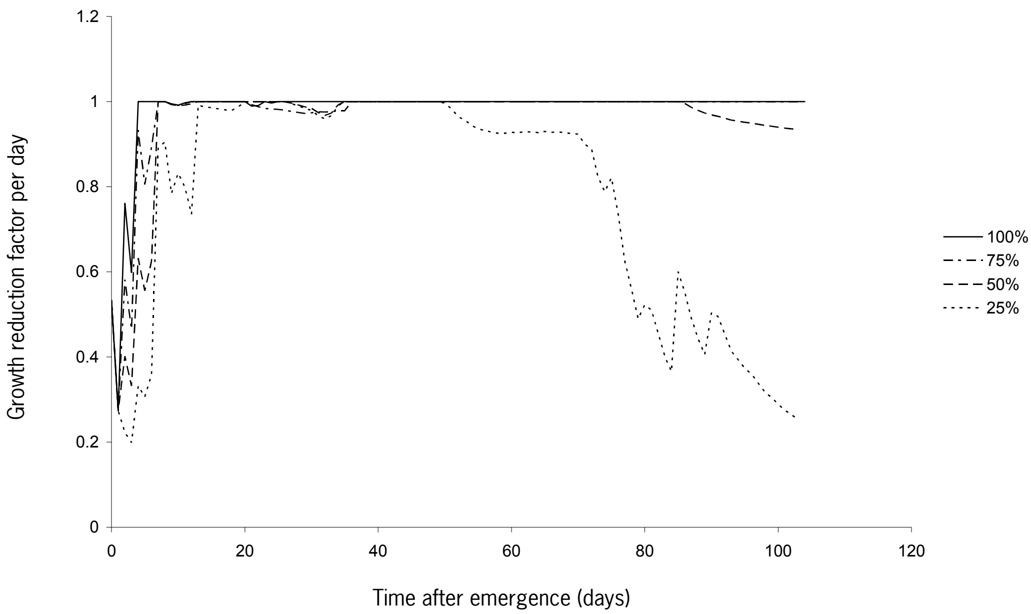

Figure 4.13. Daily growth reduction factor of sorghum (WATER1) at high density (S8) growing at four levels of water supply (100, 75, 50 and 25% of full rain).

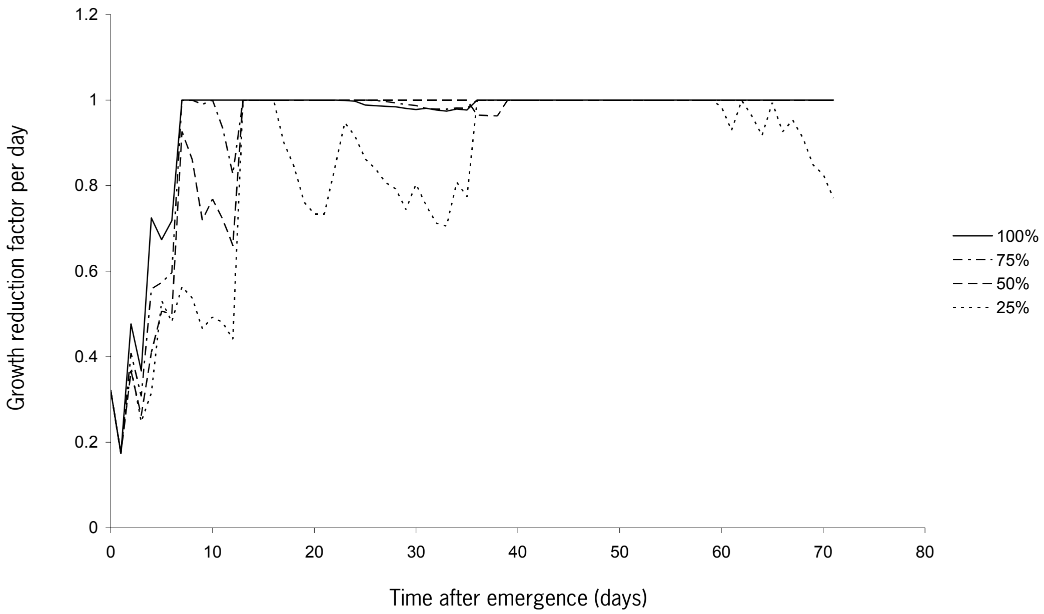

Figure 4.14. Daily growth reduction factor of cowpea (WATER2) at high density (C16) at four different levels of water supply (100, 75, 50 and 25% of full rain).

The graphs of the growth reduction factor give an insight when water shortage took place and how severe this shortage has been. At all levels of water supply there was a growth reduction during the first 35 days in sorghum and the first 40 days in cowpea. This was due to a low initial soil water content, which hampered transpiration by the crops. Reduction was more severe in cowpea than in sorghum due to higher critical water content and a higher water demand for transpiration. At a lower water supply level, it took a longer period before the growth was undisturbed. At the end of the growth period, reduction only occurred in sorghum at 50 and 25% of full water supply and in cowpea only at 25% of full water supply. Transpiration demand of sorghum was higher at the end of the growth period, so the soil water content decreased faster, causing growth reduction. The daily growth reduction factors of sorghum and cowpea differed due to (timing of) transpiration demand (Figure 4.6) and rainfall.
The implications of reduced rainfall regimes on growth, LAI and harvestable product can be seen in Figures 4.15-4.20.

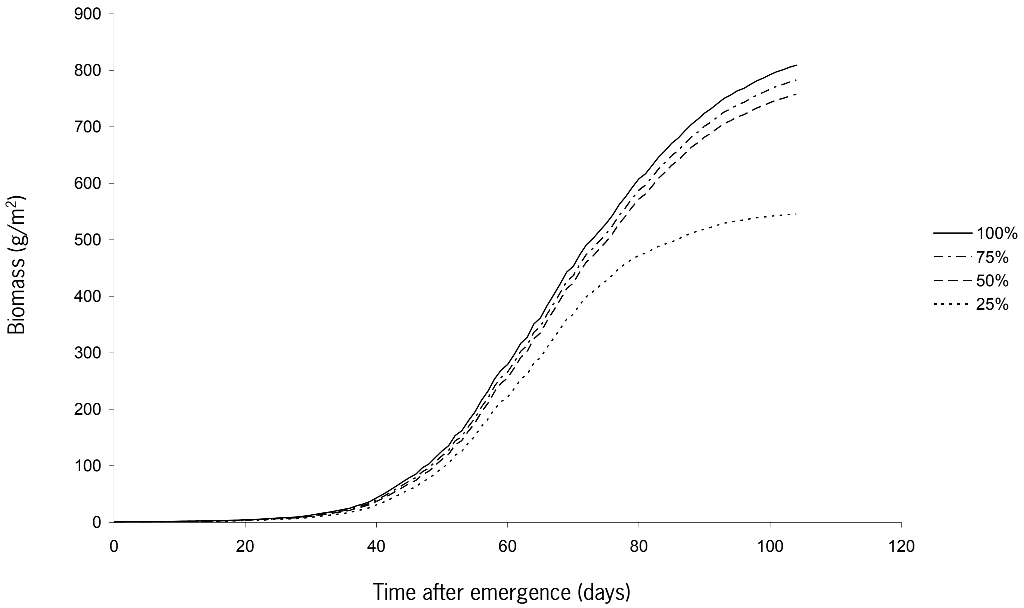

Figure 4.15. Biomass accumulation (g/m²) of sorghum, growing at 8 plants/m² (S8), at different levels of water supply (100, 75, 50 and 25% of full rain) through time.

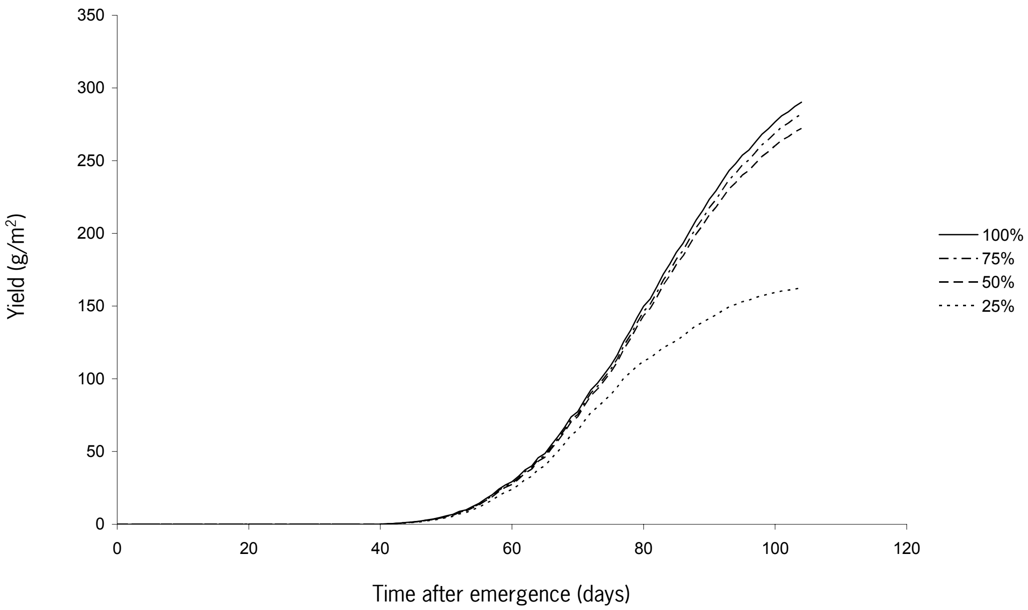

Figure 4.16. Grain yield of sorghum (g/m²), growing at 8 plants/m² (S8), at four levels of water supply (100, 75, 50 and 25% of full rain) through time.

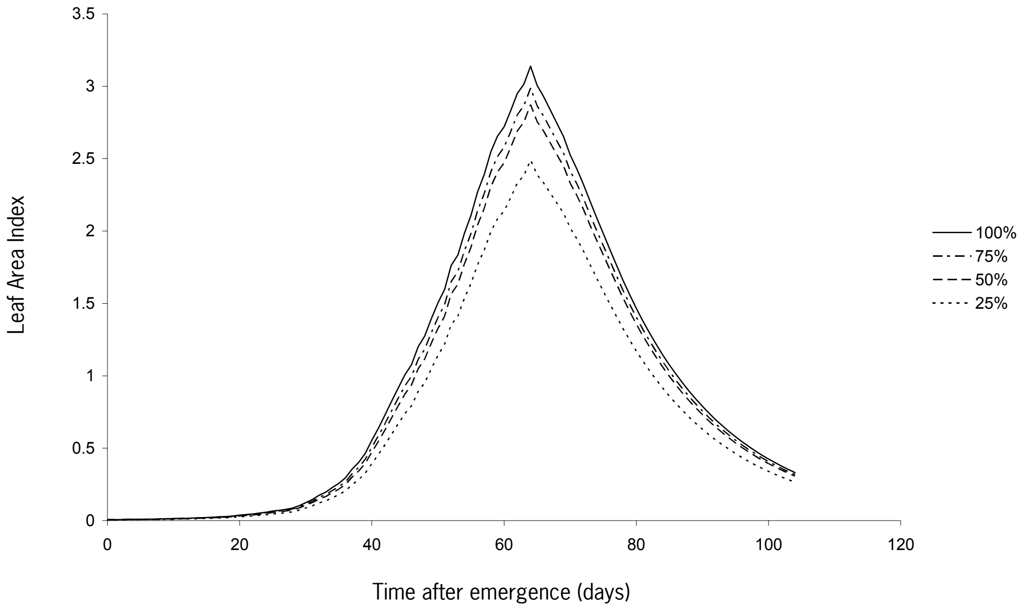

Figure 4.17. Development of the leaf area index of sorghum growing at 8 plants/m² (S8) at four levels of water supply (100, 75, 50 and 25% of full rain).

The total biomass production for sorghum was 809, 783, 758 and 545 g/m^2 at 100, 75, 50 and 25% of full rain (Figure 4.15). Growth reduction had an effect on LAI at all levels of water supply and reached a maximum of 3.1, 3.0, 2.9 and 2.5 (Figure 4.17). The harvestable organ had a yield of 290, 282, 272 and 162 g/m^2 at 100, 75, 50 and 25% of full rain, respectively (Figure 4.16). Harvest indices resulted in 0.36, 0.36, 0.36 and 0.30 at 100, 75, 50 and 25% of full rain. Comparisons for these values to literature are made below, but different densities, soils, varieties and weather made good comparisons with literature difficult.
Rees (1986a,b) did experiments in Botswana with low rainfall (84-298 mm), which is comparable to our simulations at 50 and 25% (310 and 155 mm, respectively). Most of his biomass production was equivalent to 60-225 g/m^2, maximum LAI was 1.6 and harvestable organ measured 3-61 g/m^2. The simulations results were higher, but potential evapotranspiration was lower in the simulations (700 mm in the experiments and 385 mm in the simulations), so the water demand could more easily be met. The simulated grains yields at full rainfall were in the range of grain yields found by Huda (1987), who did experiments in India in several years and places. He observed grain yields in rainy and post-rainy seasons of 80-600 g/m^2. Tefera and Tana (2002) found an average grain yield of 187 g/m^2 (depending on sorghum cultivar) for sorghum sole cropping (6.67 plants/m^2) in Ethiopia in 1996, 1997 and 1999, which is lower than the simulated yield from the model. Morris *et al.* (1990) did experiments in the Philippines during three years and obtained a sorghum yield ranging from 130-273 g/m^2 at 20 plants/m^2 depending on rainfall. The simulation results compare well to his yields. Faris *et al.* (1983) did experiments in Brazil and found sorghum yields from 189-497 g/m^2 in well fertilized plots with a high density (25 plants/m^2). The simulation results are within that range. Lightfoot and Taylor (1987) found sorghum grain yields in Botswana ranging from 31 to 347 g/m^2, depending on year, site and density. Gilbert (1996) yielded 229 g/m^2 at 5 plants/m^2 with rainfall comparable to the level of 100% water supply. Less literature is found on LAI. Hammer and Muchow (1994) found LAI-values between 0 and 7, with the majority between 2 and 3. Our results correspond to those values. In general, the results of the sorghum simulations fall within the range of values reported in literature, but true comparisons were difficult to make.

Reduction in rainfall resulted in a cowpea biomass production of 361, 345, 314 and 203 g/m^2 at 100, 75, 50 and 25% of full rain, respectively (Figure 4.18). The peak-LAI's were 1.1, 1.0, 0.91 and 0.56 at 100, 75, 50 and 25% of full rain, respectively (Figure 4.20). Harvestable organ resulted in 160, 154, 142 and 94 g/m^2 (Figure 4.19). Harvest indices were 0.44, 0.45, 0.45 and 0.46 at 100, 75, 50 and 25% of rain respectively.

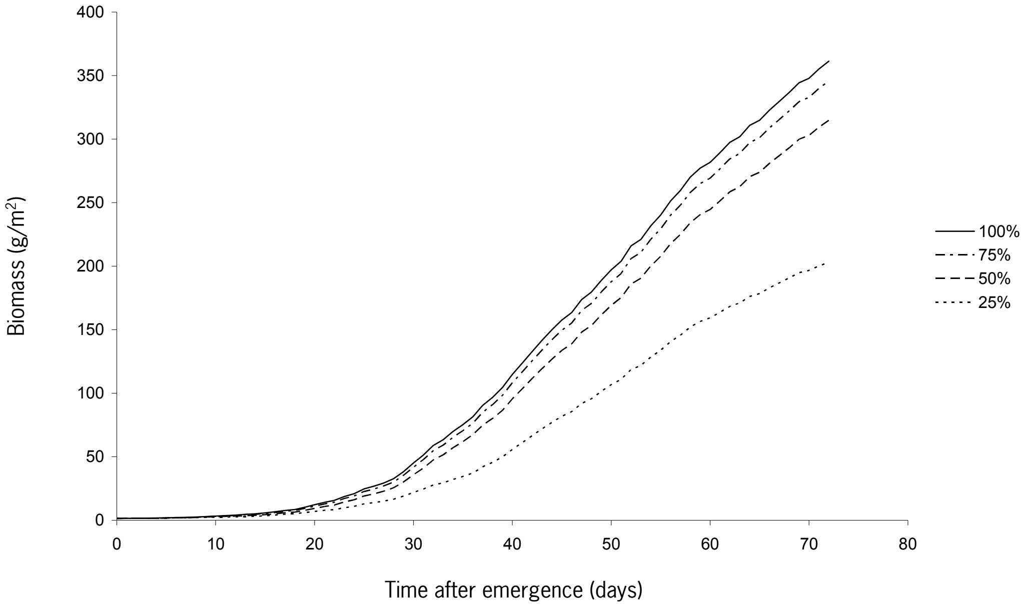

Figure 4.18. Biomass accumulation of cowpea (g/m²), growing at 16 plants/m², at four different levels of water supply (100, 75, 50 and 25% of full rain) through time.

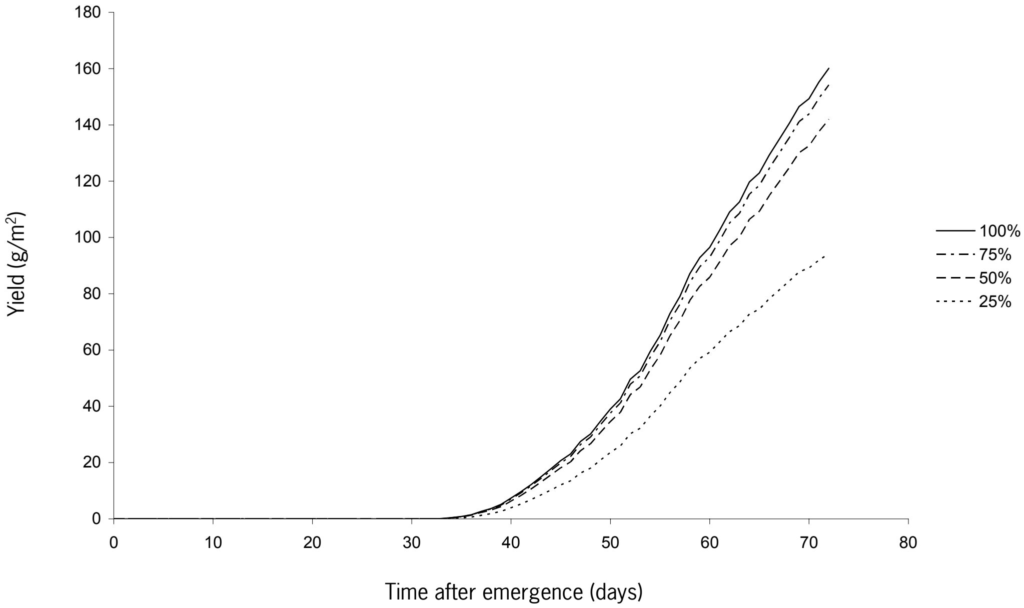

Figure 4.19. Yield of cowpea (g/m²), growing at 16 plants/m² (C16), at four different levels of water supply (100, 75, 50 and 25% of full rain) through time.

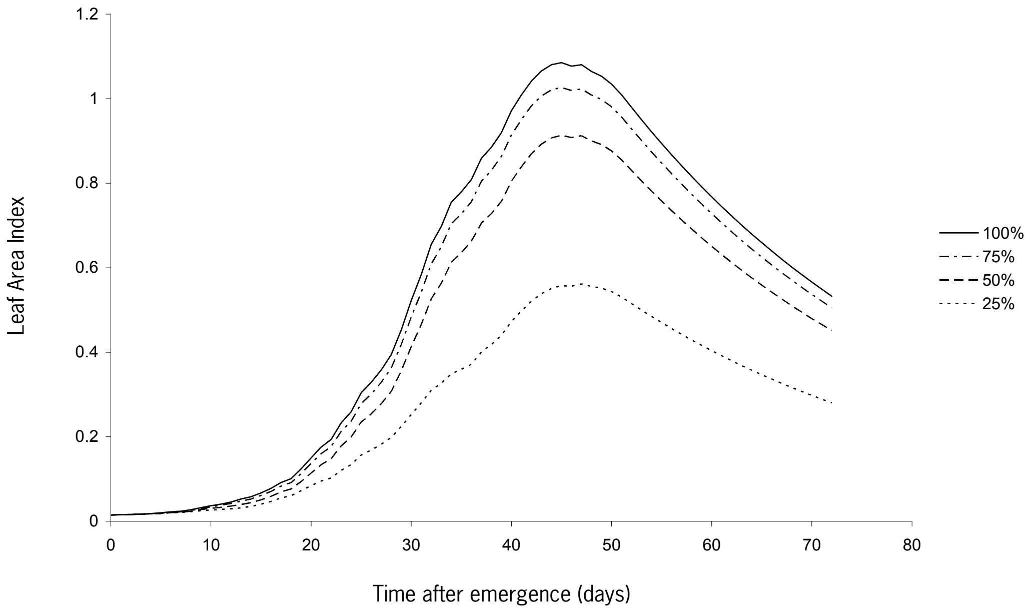

Figure 4.20. Development of the leaf area index of cowpea, growing at 16 plants/m² (C16), at four different levels of water supply (100, 75, 50 and 25% of full rain).

Reports on cowpea biomass production and harvestable organ vary widely. Rees (1986 a,b) obtained 40-192 g biomass/m^2, a maximum LAI of 0.5 and a cowpea bean yield of 25-39 g/m^2 in Botswana, which were all much lower than our results. Again, the rainfall was lower and potential evapotranspiration higher than in the simulations, which explains the lower results. Faris *et al.* (1983) obtained 11-105 g/m^2 yield in well fertilized conditions in Brazil at low density (6.25 plants/m^2), which can explain the lower results than those from the simulations. Lightfoot and Taylor (1987) had a cowpea bean yield in monoculture of 16-142 g/m^2 in Botswana, depending on year, site and density. Their higher results are in line with the simulation results at low rainfall. Morris *et al.* (1990) obtained a grain yield of 126-131 g/m^2 with 25 plants/m^2 in the Philippines, which is also in line with the simulation results at lower rainfall. The results of Idinoba *et al.* (2002) in Nigeria from cowpea monoculture experiments (6.6 plants/m^2) gave higher biomass production (600 g/m^2) and higher LAI (maximum 3.8) than the model. In the experiments, much higher radiation use efficiency was obtained than used in the model, namely 2.95 g/MJ PAR in contrast to 1.8 g/MJ PAR in the model. Muchow *et al.* (1993), who did experiments in Australian summer, found a higher biomass accumulation for cowpea, up to 1142 g/m^2 with 35 plants/m^2. Gilbert (1996) did experiments in Mali and obtained 30 g/m^2 at 5 plants/m^2. Littleton *et al.* (1979) did experiments in Nigeria and found maximum dry weights of 371-681 g/m^2, yields of 165-250 g/m^2 (assuming a shelling percentage of 20% in pod dry weight) and maximum LAI's between 3 and 5.

Specifics of water use

The transpiration in sorghum and cowpea at 75, 50 and 25% of full rain was always lower than at 100% (Figures 4.21 and 4.22), which is caused by the lower LAI's and additional transpiration reduction. Trend in the transpiration was the same, but the levels differed. The total transpirations for the four water levels were 169, 164, 160 and 117 mm for sorghum and 92, 88, 81 and 53 mm for cowpea at 100, 75, 50 and 25% of full rain, respectively.

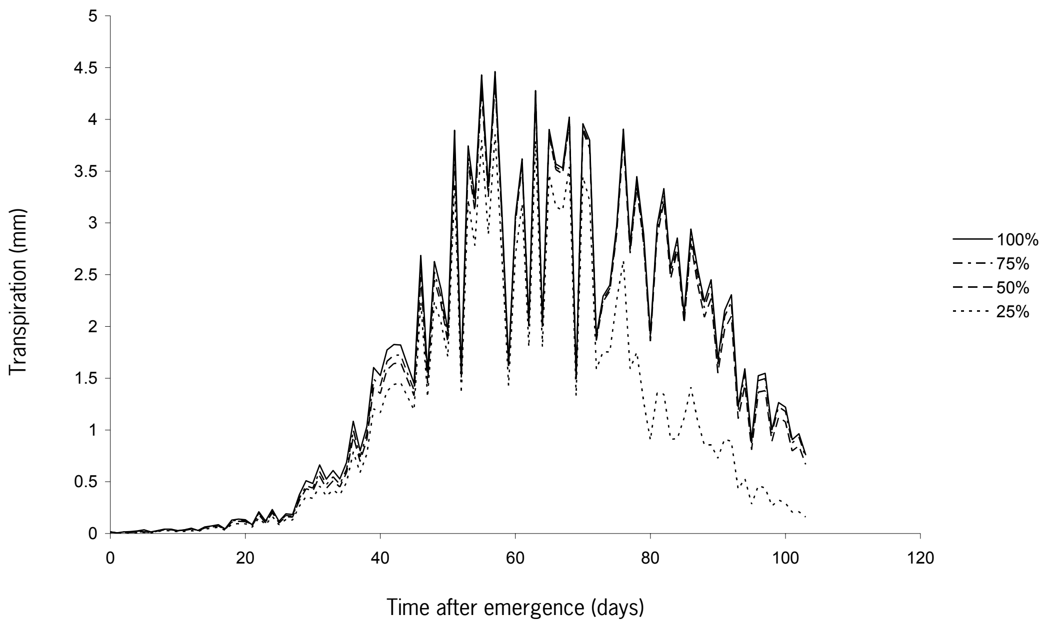

Figure 4.21. *Daily transpiration (mm) of sorghum growing at 8 plants/m² (S8), at four different levels of water supply (100, 75, 50 and 25% of full rain).*

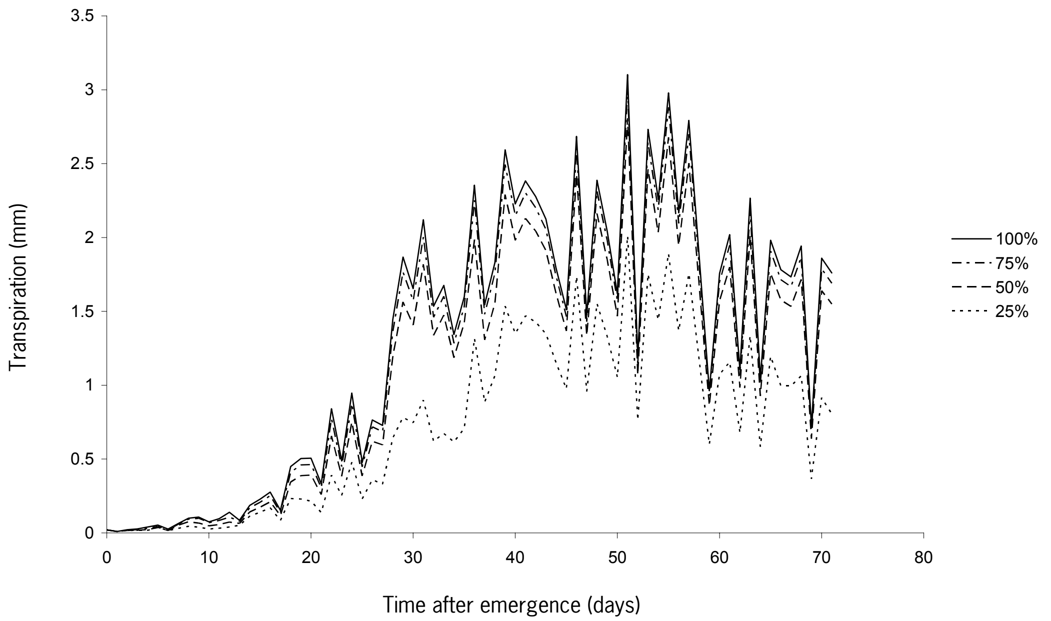

Figure 4.22. *Daily transpiration (mm) of cowpea growing at 16 plants/m² (C16), at four different levels of water supply (100, 75, 50 and 25% of full rain).*

For the evaporation, different trends were observed, because the reduction of evaporation was only depending on the water content of the top layer (Figures 4.23 and 4.24). In unlimited growth, the evaporation decreases and transpiration increases as the LAI increases. This happened in the simulation of sorghum, but in cowpea, this pattern was less visible. The evaporation at 25% of full rain was usually the lowest, but when LAI was at its top in situations with adequate water supply and hence evaporation was low, the evaporation of the low water supply crops, where the LAI was lower, could be higher. This was especially clear in the cowpea crop. Total evaporations were 146, 142, 123 and 56 mm for sorghum and 116, 114, 105 and 69 mm for cowpea at 100, 75, 50 and 25% of full rain, respectively.

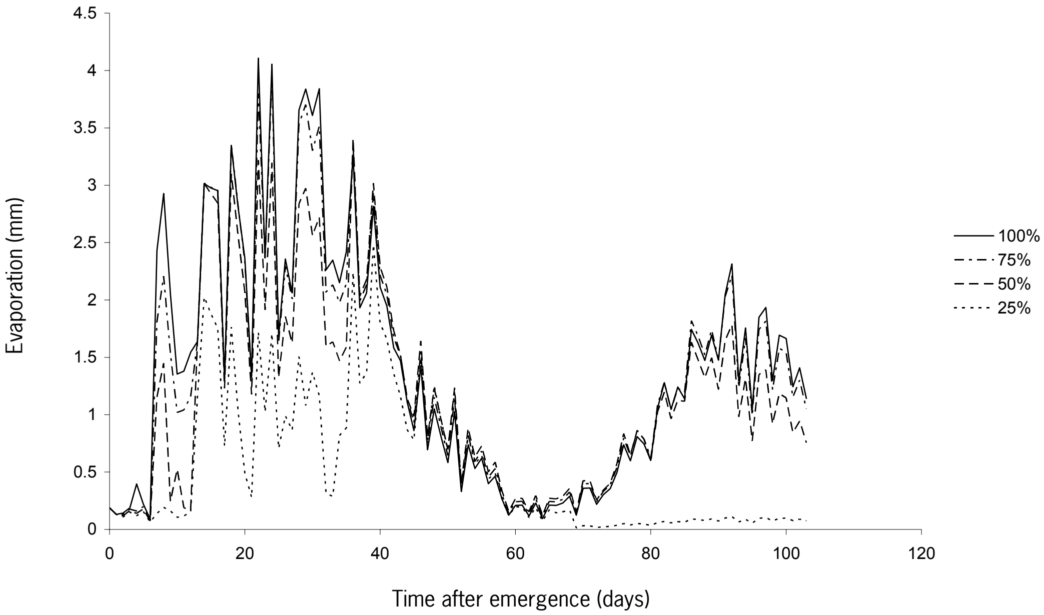

Figure 4.23. Daily evaporation (mm) under a sorghum crop growing at 8 plants/m² (S8), at four different levels of water supply (100, 75, 50 and 25% of full rain).

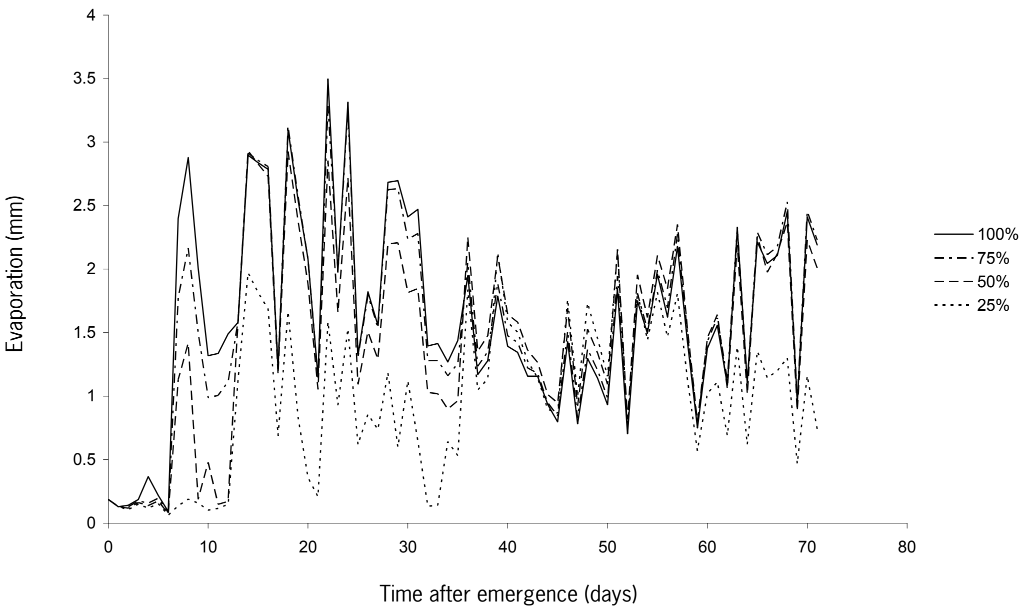

Figure 4.24. Daily evaporation (mm) under a cowpea crop growing at 16 plants/m² (C16), at four different levels of water supply (100, 75, 50 and 25% of full rain).

The total water use was 314, 306, 283 and 173 mm for sorghum and 208, 202, 186 and 122 mm for cowpea at 100, 75, 50 and 25% of full rain, respectively. As the amount of rain was decreased from 100 to 25%, the percentage of transpiration in the WU went up in sorghum and stayed approximately the same in cowpea (Figures 4.25 and 4.26). Doorenbos *et al.* (1979) reported a water use between 450 and 650 mm for 110 to 130 day sorghum. The simulated water use was lower but the water supply was not unlimited and thus water use not potential. If the water lost by percolation would be incorporated, WU would be closer to the value mentioned by Doorenbos *et al.* Morris *et al.* (1990) found a water use of 167-257 mm in sorghum monocultures and 164-182 mm

in cowpea cultures, depending on the year. Water use of the simulation results at 50 and 25% of normal rain fell into this range. Rees (1986b) observed water use in the sorghum monoculture between 124 and 380 mm, which is in the range found with the model, although his biomass production was lower. For cowpea, he found water use between 127-204 mm, which also fit within the model results. Rees found ratios of actual/potential evapotranspiration of around 0.2. In the model, this ratio decreased from 0.82 to 0.45 in sorghum and 0.78 to 0.44 in cowpea when rainfall decreased from 100 to 25% of the actual amount.
In both crops, percolation only occurred at 100 and 75% of full rain and was 225 and 95 mm, respectively (Figures 4.25 and 4.26). The decrease in rainfall was mainly used for a decrease in percolation and change of soil water. More water was added to the soil in cowpea than in sorghum. However, part of the soil water left after the cowpea crop was not available to that crop (water between 40 and 60 cm depth). At 25% of actual rain, the change in soil water content was negative in sorghum. This means that the growth of the plants was also depending on the amount of water in the soil at the start of the growth. If the initial amount of soil water would be lower, growth reduction would be higher. Some rain had already fallen before the growth of the crops starts (58 mm), so the estimation of 0.15 volume fraction soil water is not unrealistic. The figures clearly show that as water supply diminishes a little, percolation and change in soil water were first diminished, while transpiration was kept at nearly the same level as at full water supply.

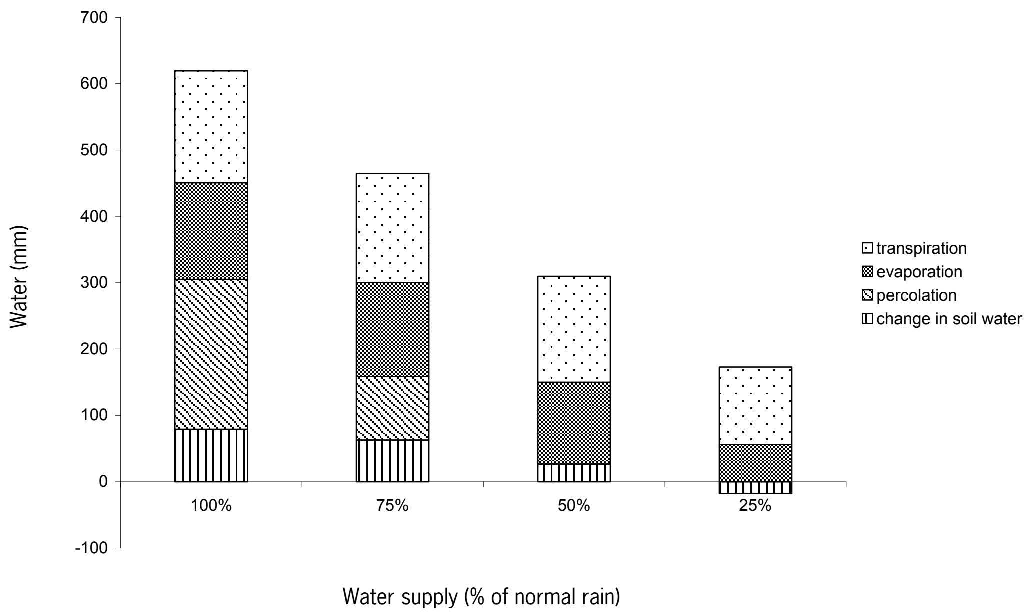

Figure 4.25. The absolute partitioning of the water supply over soil water content, percolation, transpiration and evaporation at the end of the growing period of sorghum, growing at 8 plants/m² (S8), at four different levels of water supply.

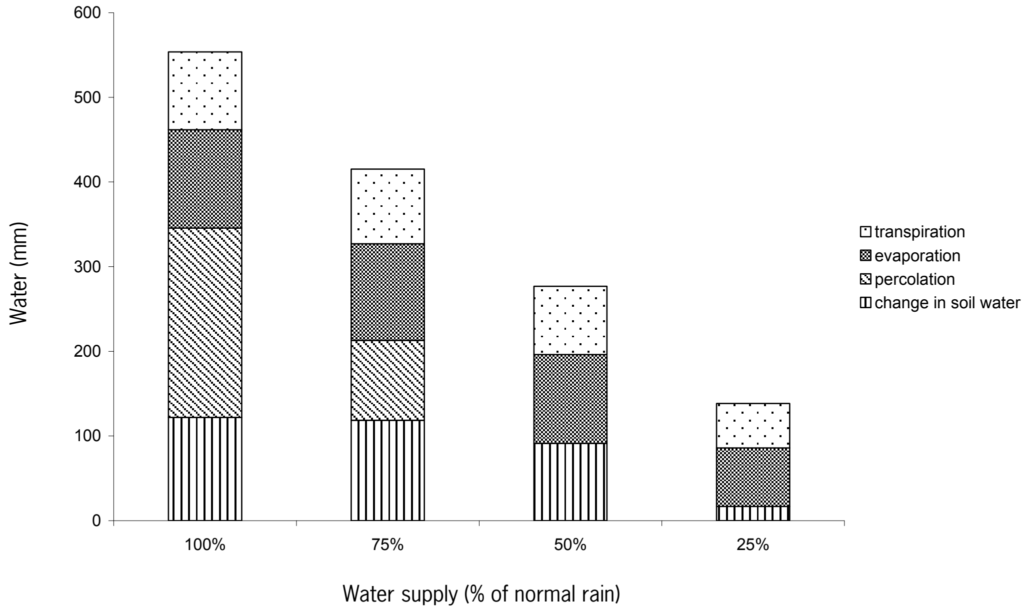

Figure 4.26. The absolute partitioning of the water supply over change in soil water content, percolation, transpiration and evaporation at the end of the growing period of cowpea, growing at 16 plants/m² (C16), at four levels of water supply.

The water used for evapotranspiration was more efficiently used in sorghum than in cowpea (Figures 4.27 and 4.28). In sorghum, the water use efficiency increased with decreasing rainfall, while in cowpea, there was a slight decreasing trend of WUE with decreasing rainfall. The fraction transpiration in the WU (transpiration + evaporation) was nearly the same in every simulation for cowpea, while it increased for sorghum. The growth reduction was more severe in cowpea, which caused in total a decreasing WUE with decreasing water supply. WUE for the harvestable organ were in line with the values derived from Morris *et al.* (1990), which had WUE of 0.00078-0.0011 g yield/g water for sorghum and 0.00077-0.00086 g yield/g water for cowpea.
However, in the definition of water use, only the transpiration and evaporation are regarded. The water lost by percolation, which was quite considerable in the simulations at 100 and 75%, is not regarded as water use, although it was lost from the system. When percolation would be included in the water use, the water use efficiencies would be 0.0015 and 0.0019 g dm/ g water for sorghum at 100 and 75% of rainfall and 0.0008 and 0.0012 g dm/g water for cowpea at 100 and 75% of rainfall, respectively. The differences in the water use efficiency for the harvestable organ at the different amounts of rain were very small, with the highest value at 50% of normal rain for sorghum and 25% of normal rain for cowpea.

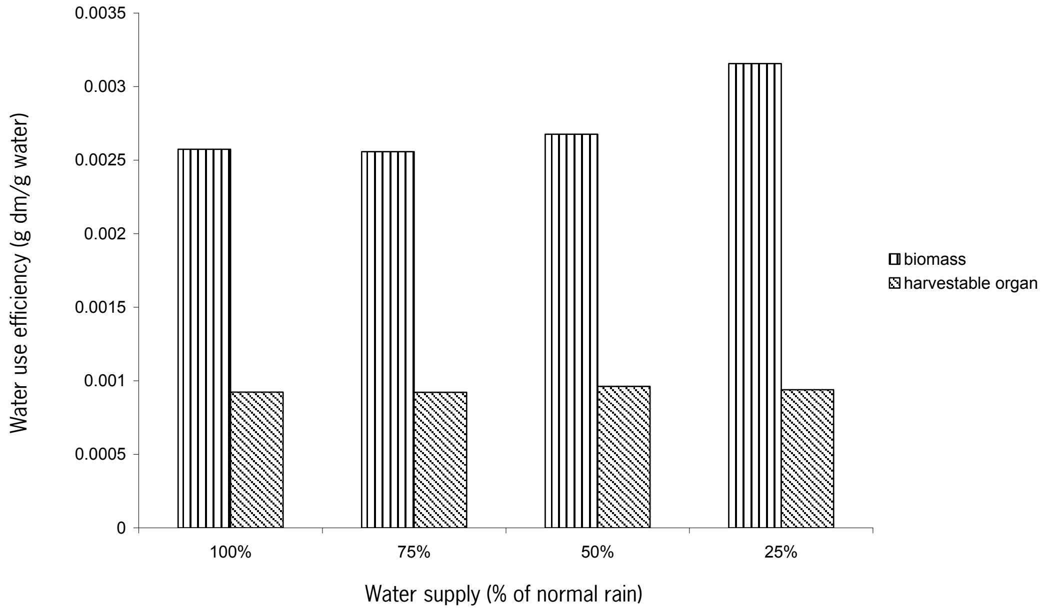

Figure 4.27. Water use efficiencies for total biomass production (g dm/g water) of sorghum (8 plants/m²) at the four levels of water supply (100, 75, 50 and 25% of full rain).

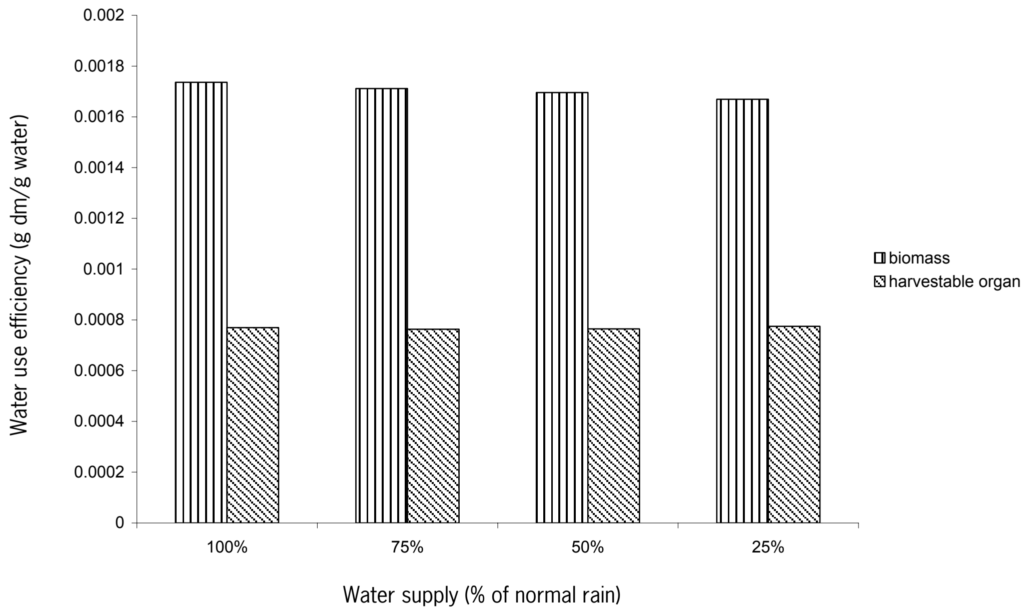

Figure 4.28. Water use efficiencies for harvestable organ (g harvestable organ/g water) of cowpea (16 plants/m²) at the four levels of water supply (100, 75, 50 and 25% of full rain).

Water in soil

Figures 4.29 and 4.30 show the water in the total soil profile (0-60 cm) under a sorghum and cowpea crop, respectively at four different levels of water input. In Figures 4.31 and 4.32, the plant available water is shown.

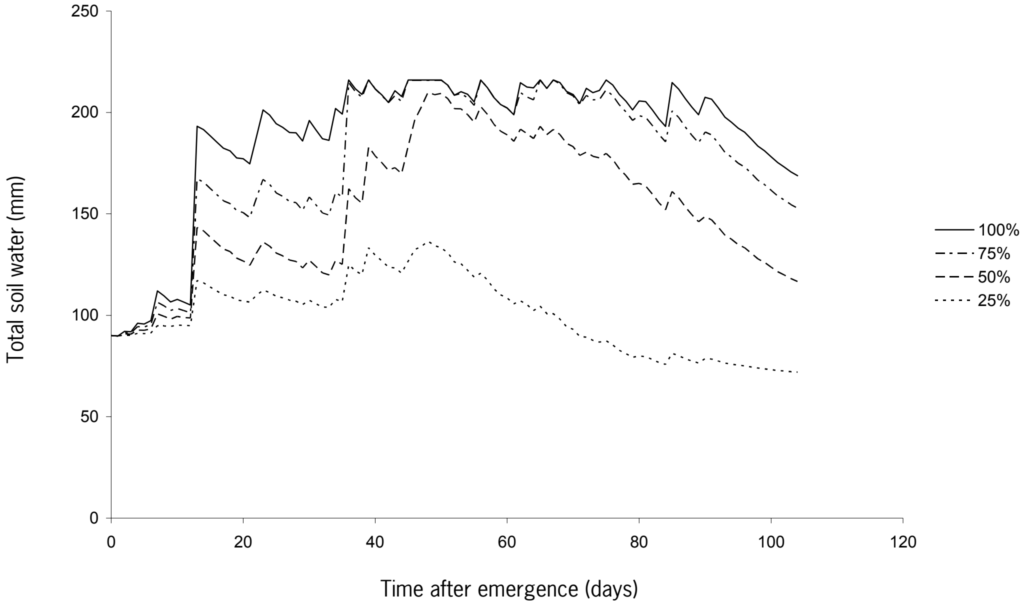

Figure 4.29. Water in total soil profile under sorghum (8 plants/m²) growing at 100, 75, 50 and 25% of full rain.

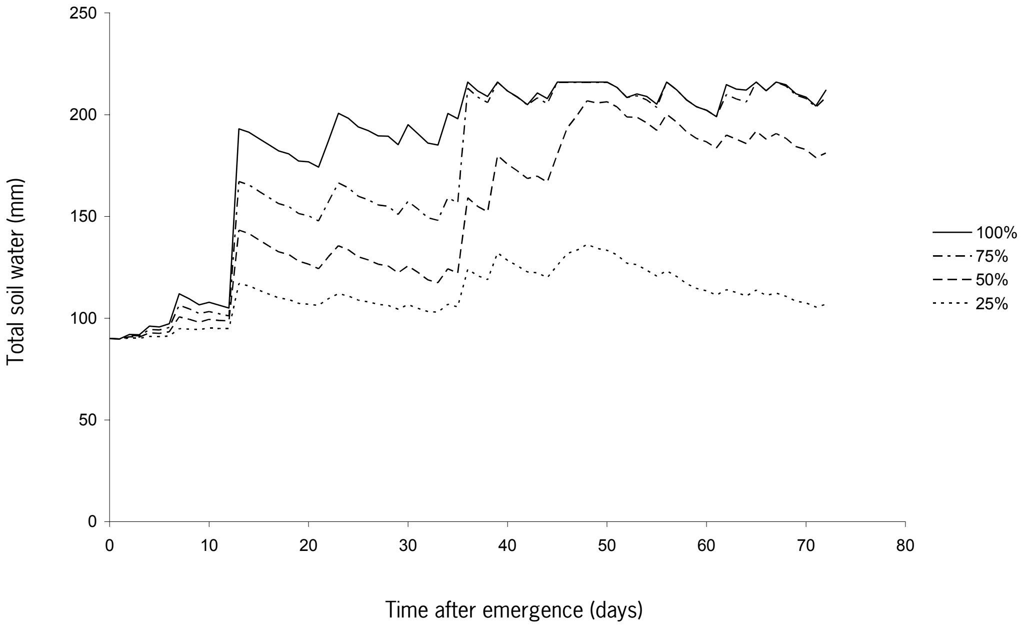

Figure 4.30. Water in total soil profile under cowpea (16 plants/m²) growing at 100, 75, 50 and 25% of full rain.

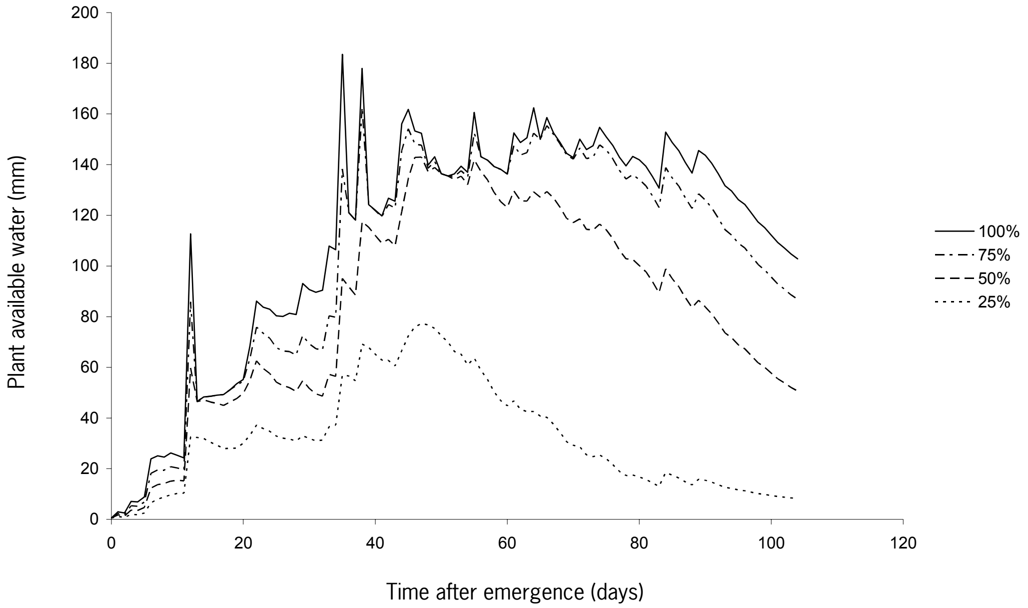

Figure 4.31. Plant available water in the rooted zone of sorghum (S8) growing at 100, 75, 50 and 25% of full rain.

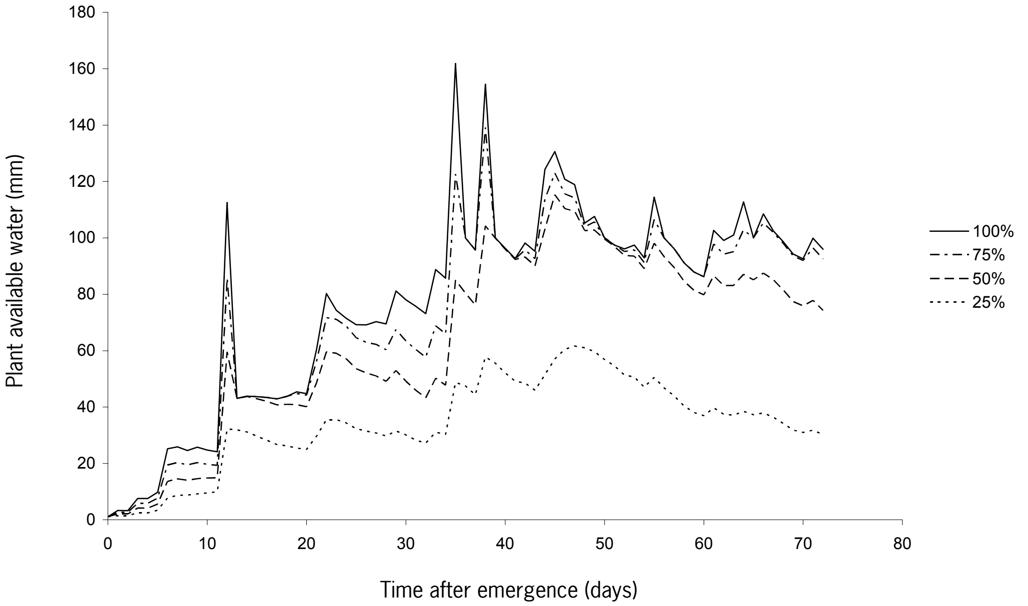

Figure 4.32. Plant available water in the rooted zone of cowpea (C16) growing at 100, 75, 50 and 25% of full rain.

For both crop species, the trend in the total amount of soil water was nearly the same for all the four levels of water input, though the actual amounts differed (Figures 4.29 and 4.30). For both crops, soil water content between 100 and 75% of full rain didn't differ much; difference between 75 and 50% and between 50 and 25% was much greater. At then end of the growing period, the soil water content in sorghum for the simulation with a water supply of 25% decreased slower than in the other stands. This can be explained by the fact that hardly any water was available to the crop. Consequently, transpiration was hampered and the decrease in soil water content was slowed down.

At the end of the growing period there was still a lot of plant available water in the three highest water supply levels, but at the water supply level of 25%, the plant available water for sorghum had decreased till just above zero, which makes crop growth hardly possible (Figure 4.31). In cowpea, there was more water available for the crop at 25% of normal rain (Figure 4.32). This is reflected in the growth reduction factors presented in Figures 4.13 and 4.14, which was close to zero at that time for sorghum, while the reduction was much lower in cowpea. From this can also be derived that water was not limiting growth in the two higher levels of water supply and that water could be used more efficiently when a higher density was used. Also extension of the growing season or other practices to increase productivity would help to increase the use of water. Cowpea could have used the water better if the rooting depth was greater or the critical water content lower.

Radiation interception

With reduction of water supply, radiation interception was only marginally decreased compared to the growth (Figures 4.33 and 4.34). For example, growth reduction in sorghum was 33% while intercepted radiation was reduced by 14% when water supply decreased from 100 to 25% of normal rain. This reduction in growth had thus two causes: the lower radiation interception and the growth reduction by water stress. At the end of the growth period, radiation interception in cowpea was still linearly increasing in cowpea, while it was already decreasing in sorghum. This is due to the high decrease in sorghum LAI. At full water supply, the cumulative intercepted radiation of cowpea was still lower than found by Muchow *et al.* (1993). Their crop intercepted up to 524 MJ PAR/m^2, which is nearly twice as high as the values found here, but their crop was characterised with a higher LAI. Crop duration was the same as in the simulations (70 days).

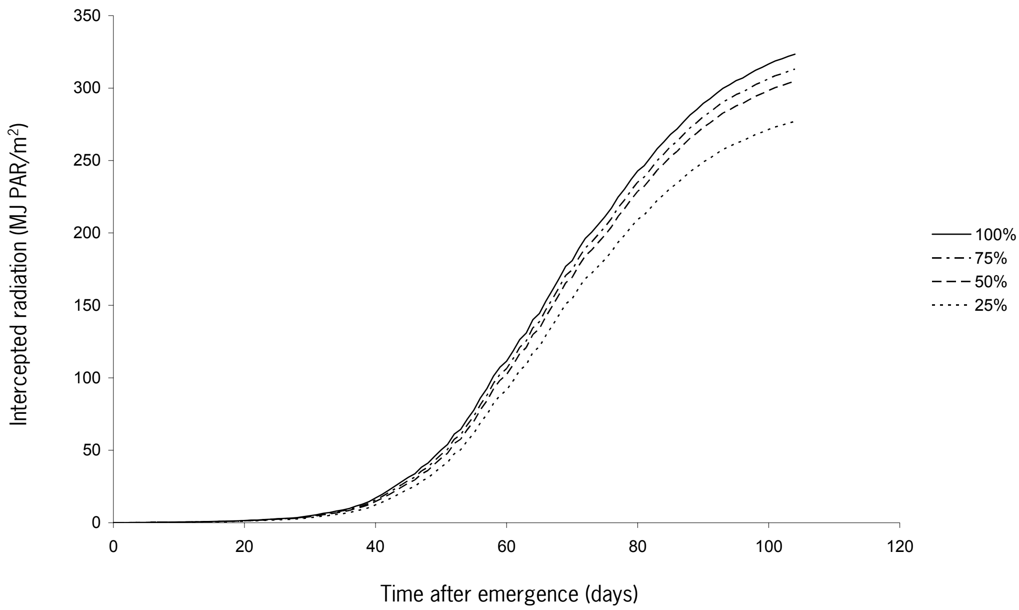

Figure 4.33. The cumulative intercepted radiation (MJ PAR/m^2) for sorghum grown at 8 plants/m^2, at four different levels of water supply.

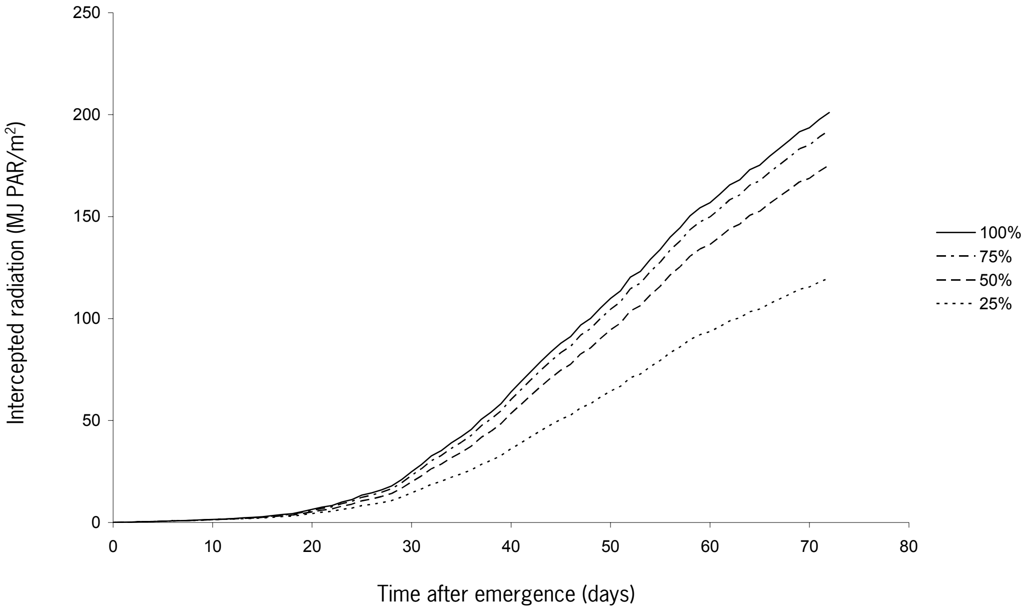

Figure 4.34. The cumulative intercepted radiation (MJ PAR/m²) for cowpea grown at 16 plants/m², at four different levels of water supply.

LER, ΔWU and ΔWUE

The high density pure stands always had an advantage over the low density pure stands (LER>1) at all levels of water supply (Figures 4.35 and 4.36). The LER for biomass was always higher than for harvestable organ. The harvestable organ was formed at the end of the growth period, when intraspecific competition was more severe thus having sub-optimal growth.

Sorghum and cowpea showed a different behaviour in the LER at different levels of rain. Cowpea had a continuous increase in $LER_{biomass}$ with decreasing rainfall, while sorghum had the highest $LER_{biomass}$ at 50% of normal rain. At 25% of actual rain, the biomass decreased proportionally more in the high density than in the low density. The high density had a higher transpirational demand due to a higher LAI. If growth reduction occurred, this had more impact on production in the high density and consequently lower accumulation of biomass occurred in the high density than in the low density. This caused a slight decrease in the LER. The LER_{yield} also had the highest value at 50% in the sorghum, while it was continuously increasing in cowpea.

The water use at high density increased compared to the low density in both crops at all levels of water supply. The increase was 0.5% at 100% of normal rain and 2.4% at 25% of normal rain.

The increase in water use efficiency for biomass was 29, 30, 29 and 24% for sorghum and 45, 47, 49 and 56% for cowpea at 100, 75, 50 and 25% of full rain. For harvestable organ, the advantages of water use efficiency from the high density over the low density were lower. The increase in WUE_{harv} was 25, 26, 25 and 11 in sorghum and 39, 41, 43 and 51% for cowpea at 100, 75, 50 and 25% of normal rain, respectively. This means that for all high density crops at all four water levels, the water use efficiency was higher than at the low density crops. The trends in the increase of the WUE with respect to the low density are the same as the trend of the LER: sorghum has the highest values in the first three levels of water supply and the WUE decreased at 25% of water supply, while cowpea had a continuous increase in the change of WUE with decreasing water supply. This can be explained by changes in WU and LER. For cowpea, the increase in WU (ratio of the WU of high and low density) is much less than the increase in LER (ratio of the production of high and low density), which causes an increase in the WUE (ratio of the productivity and water use).

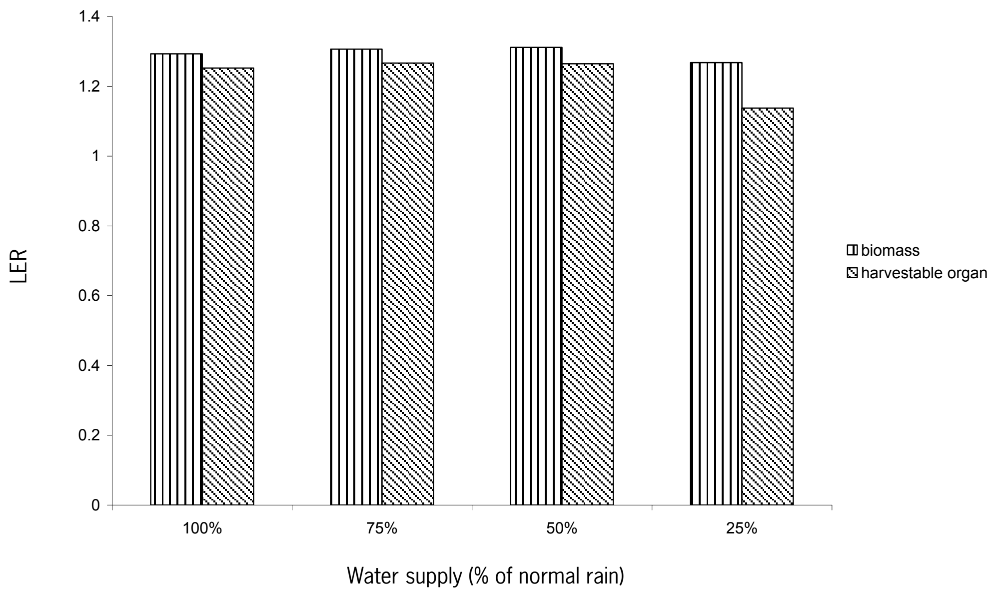

Figure 4.35. The Land Equivalent Ratio (LER) of high density sorghum at four different levels of full rain.

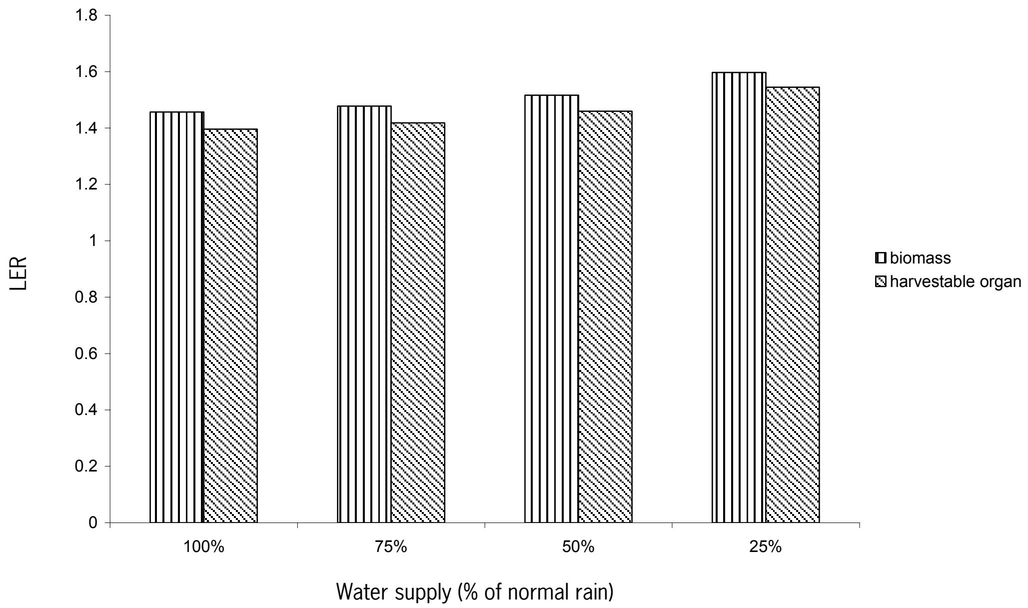

Figure 4.36. The Land Equivalent Ratio of high density cowpea at four different levels of full rain.

4.3 Conclusions

Growth in the current situation was not potential, but reached ± 6 and 22% lower yields in sorghum and cowpea, respectively. The development of cowpea took a shorter period than that of sorghum. The crop accumulated less biomass, had a lower LAI and lower harvestable yield. Cowpea leaf area grew faster and therefore reached its peak demand in water for transpiration earlier than sorghum. The high density stands had an advantage over the low density stands, because more biomass and yield were produced (LER>1) with the same amount of water and, consequently, made better use of the resources water and radiation.

Cowpea and sorghum reacted differently on the different levels of water supply, due to timing of rainfall and demand of water needed for transpiration. For both crops, all levels of water supply had an effect on biomass accumulation,

mainly due to growth reduction at the start and also at the end of growth at 50 and 25% of water supply.
Growth reduction at 25% of rainfall was 33 and 43% of the growth at 100% of rainfall for sorghum and cowpea, respectively. Plant available water gradually decreased and was nearly zero at the end of the growing period in sorghum, while cowpea could have used more water. Radiation interception diminished due to growth reduction early in the season. The high density stands had an advantage over the low density stands at all amounts of rain (LER>1), but with deceasing water input, this advantage increased in cowpea while it showed an optimum in sorghum at 50% of rain. This is caused by the fact that the sorghum plants had a higher demand for transpirable water and at higher density, the amount of rain was not enough to provide a high density stand with the sufficient amount of water.
From the point of water use efficiency, the production per gram of water was the highest at the lowest amount of water supplied in sorghum. However, production was very low, so aiming for this level of water use efficiency is not advisable. Cowpea WUE was slightly decreasing with decreasing water supply. At high water supply levels, a lot of water is lost through percolation due to unmatching demand and supply of water. For the production of harvestable organ, the WUE hardly differs between the levels of water supply.
The values of LER, ΔWU and ΔWUE indicated that even higher densities could be grown, which would obtain a higher yield with the same amount of supplied water. This was also indicated by the Figures 4.29 and 4.30, where there was water left in the soil after the completion of crop development, which could have been used if more plants where grown.

5. Results and analysis of model simulations II: standard intercrops

In this chapter, the behaviour of the intercrops S8C16, S8C8 and S4C8 is studied: first at full rain, than at the four different levels of rainfall. Results are given as described in chapter 3.

5.1 Standard simulations at full rain

Total biomass production and harvestable yield

The growth compared to pure stands of both sorghum and cowpea was reduced, due to competition for light with the other crop. Water stress occurred in all intercrops at full rain and it was higher in the cowpea than in sorghum. The highest sorghum biomass (773 g/m^2) was obtained in the stand with high density of sorghum and the lowest competition from cowpea (S8C8), followed by the S8C16 and S4C8 intercrops (668 and 526 g/m^2, respectively) (Figure 5.1). The highest cowpea biomass (220 g/m^2) was obtained in the S8C16 intercropping, followed by the S4C8 and S8C8 intercrops (170 and 136 g/m^2, respectively). From these results, it became clear that the LAI of sorghum posed a constraint on the growth of cowpea and vice versa and that cowpea growth was more reduced than sorghum growth.

The sorghum in S8C8, S8C16 and S4C8 had a yield of 262, 244 and 198 g/m^2, respectively, so the highest sorghum density with the lowest cowpea density gave the highest yield. This resulted in harvest indices of 0.37, 0.36 and 0.37 in S8C16, S8C8 and S4C8, respectively, which were around the harvest indices in the pure stands (0.36). The cowpea had the highest yield in the highest density (71 g/m^2 in S8C16), followed by S4C8 and S8C8 (64 and 45 g/m^2, respectively) (Figure 5.2). The harvest indices for cowpea were lower than in the pure stands, which were 0.45; HI was 0.33, 0.33 and 0.38 in S8C16, S8C8 and S4C8, respectively.

The development of the LAI showed the same trend as the growth of the biomass with respect to the order of the LAI of the different intercrop systems (Figure 5.3). The leaf areas of the crops have a complementary behaviour: when the cowpea leaf area is developing, sorghum leaf area is still low and when the sorghum leaf area comes to full development, the cowpea leaf area is already decreasing.

Comparisons of the growth to unlimited growth are difficult, because growth reduction in one crop gave an additional growth in the other crop. For example, the unlimited growth results in 763 g/m^2 for sorghum in S8C8, while it is 772 g/m^2 the present situation. This is due to a growth reduction of cowpea in the first phase of growth with results in less leaf area and thus more light interception and hence more growth in sorghum. Cowpea biomass is 136 g/m^2, while it would be 182 g/m^2 in the undisturbed growth of the S8C8 intercrop.

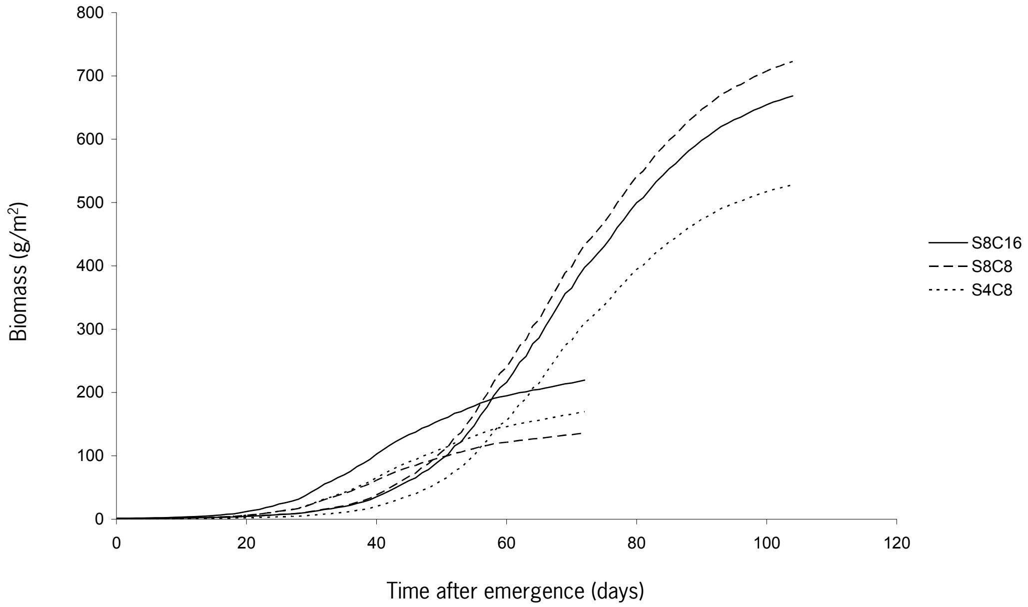

Figure 5.1. *Biomass accumulation (g/m²) of sorghum and cowpea in the three intercropping densities through time. The lines with the same pattern belong to the same intercropping; the lines with a short duration belong to cowpea, with a long duration to sorghum.*

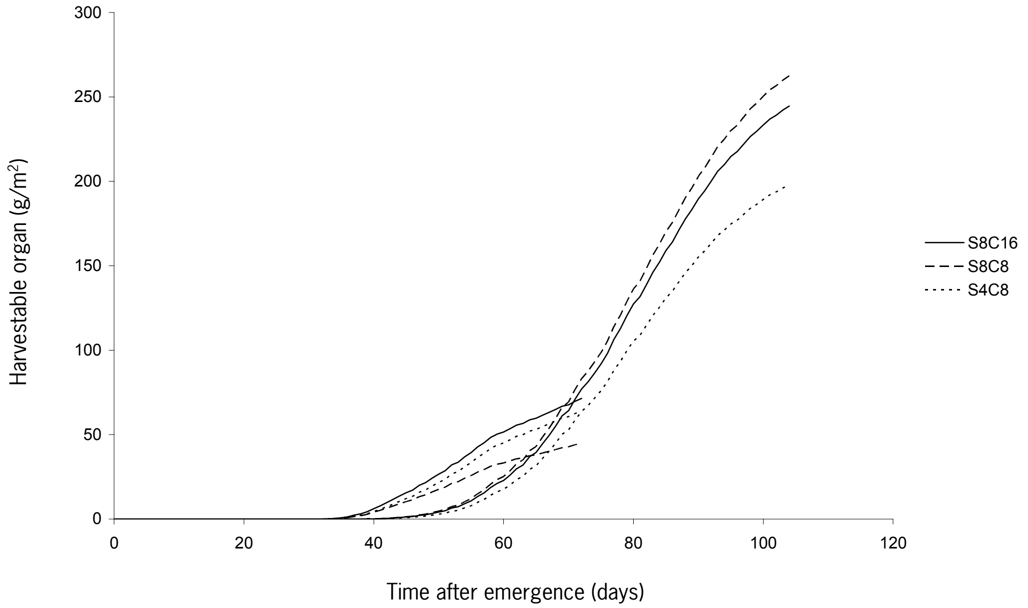

Figure 5.2. *Harvestable organ (g/m²) of sorghum and cowpea in three intercropping densities through time. Lines with the same pattern belong to the same intercropping; the lines with a short duration belong to cowpea, with a long duration to sorghum.*

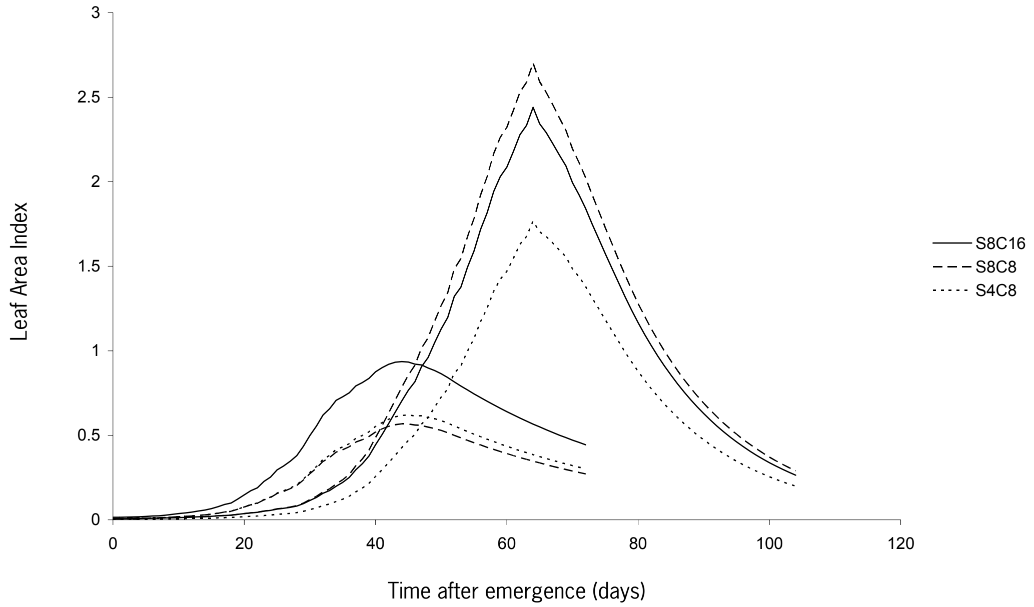

Figure 5.3. *Development of the Leaf Area Index of sorghum and cowpea in the three intercropping densities. Lines with the same pattern belong to the same intercropping; the lines with a short duration belong to cowpea, with a long duration to sorghum.*

Specifics of water use

When the LAI increased, the transpiration of the S8C16 intercropping was the highest, due to a higher total LAI. When transpiration decreased during leaf senescence of sorghum, the transpiration was highest in S8C8, which had the highest sorghum-LAI. The transpiration in the S4C8 intercropping was always the lowest (Figure 5.4). Total transpiration was 191, 183 and 157 mm for S8C16, S8C8 and S4C8 respectively. Cowpea transpiration was 30, 21 and 30% of the total transpiration in S8C16, S8C8 and S4C8, respectively.

Evaporation showed the opposite trend of transpiration (Figure 5.5); high in the beginning, decreasing as the LAI increased and a small increase at the end. During the first seven days, evaporation was low due to low soil water content. Evaporation was higher as the total LAI was lower. The total evaporation was 109, 123 and 144 mm for the S8C16, S8C8 and S4C8 intercropping systems, respectively. Evaporation was lower than in the pure stands of sorghum, due to higher LAI throughout the growing season (Figure 5.3), while transpiration was higher.

Total water use resulted in 300, 306 and 301 mm for S8C16, S8C8 and S4C8, respectively. The differences in total water use are caused by the fact that potential evaporation was calculated in a slightly different way than the potential transpiration (see equation 3.10 and 3.11), so the amount of water not used for transpiration was not automatically used for evaporation.

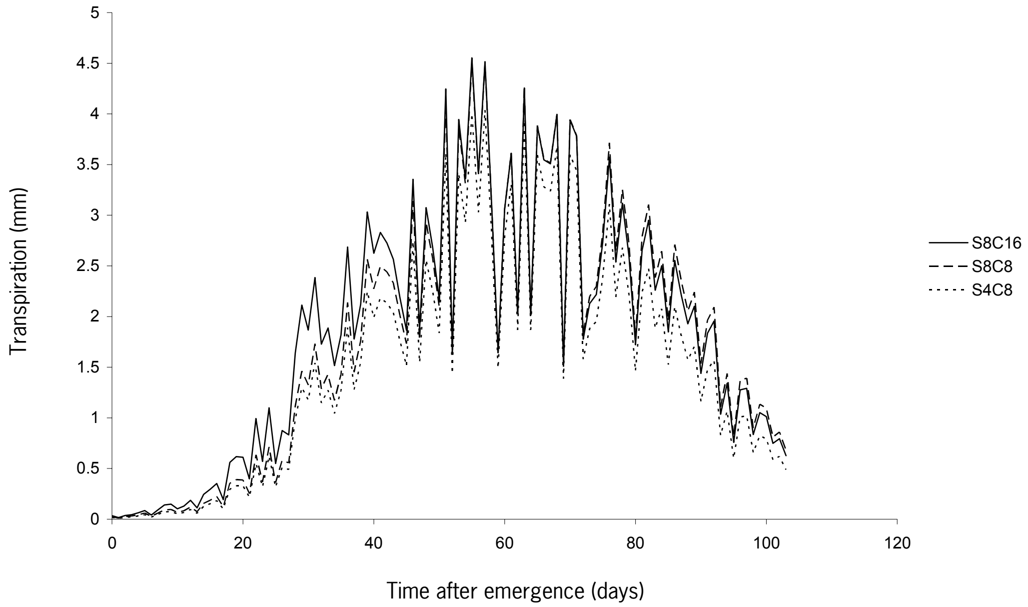

Figure 5.4. *Daily transpiration (mm) in the three intercropping systems.*

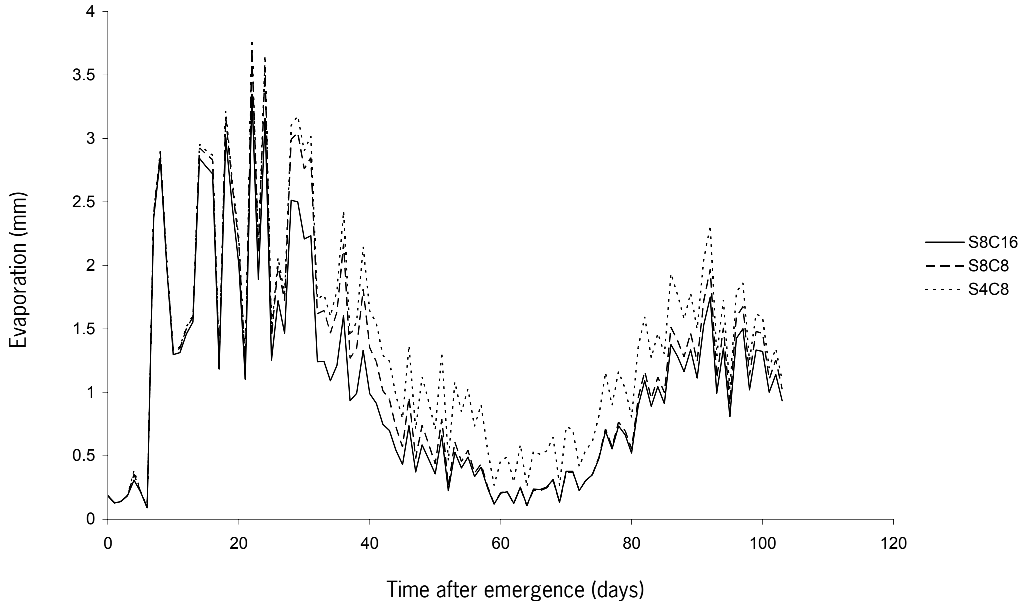

Figure 5.5. *Daily evaporation (mm) over time in the three intercropping systems.*

Figure 5.6 shows the distribution of the rainfall over several destinations at the end of the growing season. The fraction evaporation increased as the overall density decreased. Change in soil water and water lost through percolation was nearly the same in all intercropping systems; percolation and change in soil water were slightly higher than in pure stands. In absolute terms, the percolation was ± 228 mm. The average increase in soil water was around 89 mm.

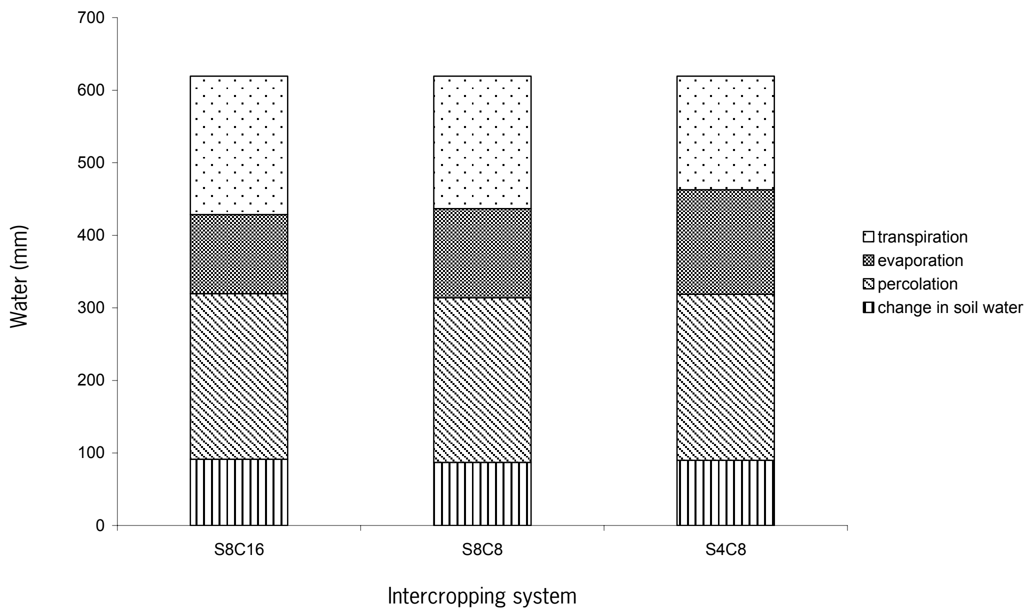

Figure 5.6. *The distribution of the rainfall partitioned over a) change in soil water, b) percolation, c) transpiration and d) evaporation at the end of the growing period for the three intercropping systems.*

The WUE's for both biomass and harvestable organ were higher than the WUE's from the pure stands of sorghum and cowpea (Figure 5.7). The water use efficiency decreased as the overall plant density decreased, both in biomass and in harvestable organ. Production in S8C16 was highest and lowest in S4C8, while water use was nearly similar in all intercrops, which resulted in the lowest water use efficiency for S4C8.

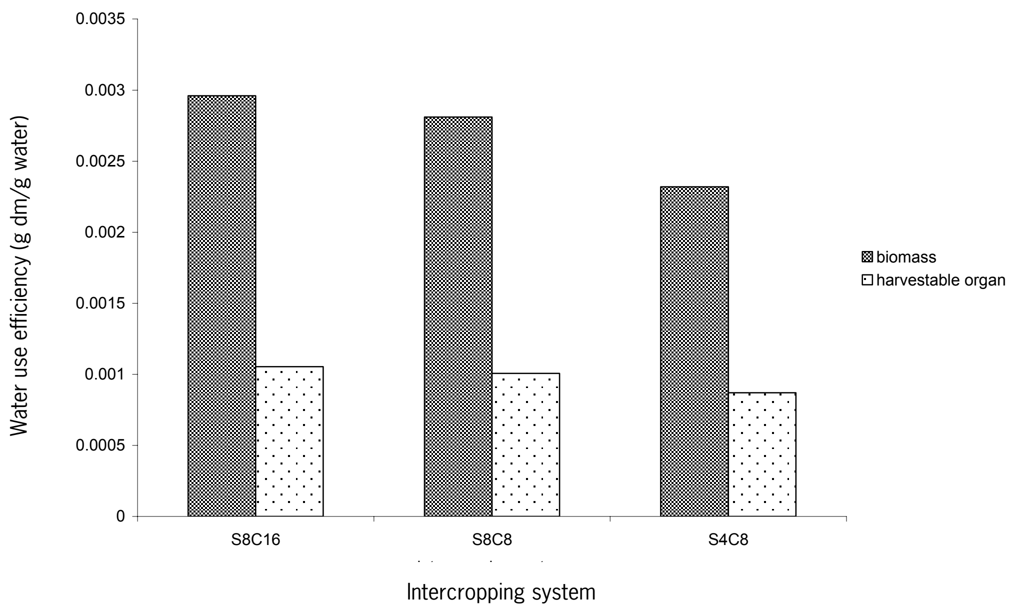

Figure 5.7. *The water use efficiencies for biomass and harvestable organ (both in g dm/g water) for the three intercropping systems.*

Water in soil

Figure 5.8 shows the total amount of water in the soil profile, the plant available water for sorghum and the plant available water for cowpea. There was hardly any difference in amount of soil water between the three systems. Only at the end of the growth period, the amount of total soil water and hence plant available water for sorghum differed slightly.

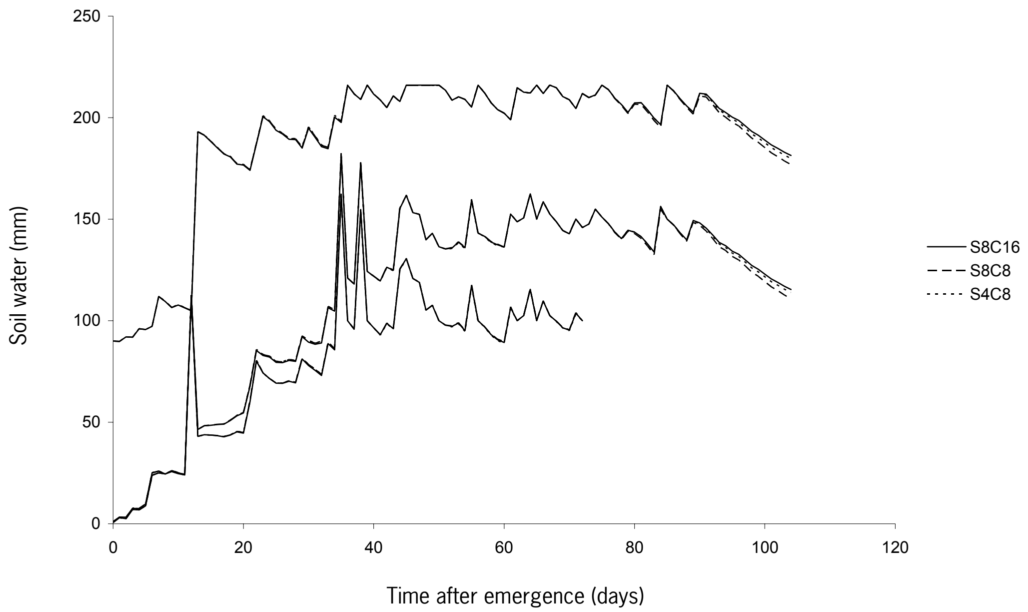

Figure 5.8. *The total amount of soil water (upper lines), the plant available water of sorghum (middle set of lines) and the plant available water for cowpea (lower lines) in the three cropping systems.*

Radiation interception

The cumulative intercepted radiation showed the pattern which was expected (Figure 5.9); the intercropping systems with the highest density, S8C16, had the highest amount of intercepted radiation, followed by the middle and low density intercrop. Total intercepted radiation was 389, 365 and 305 MJ PAR/m^2 for S8C16, S8C8 and S4C8, respectively. Compared to the pure stand simulations, the total intercepted radiation was 127, 119 and 99.7% of the radiation interception of a pure stand of sorghum with 8 plants/m^2 (S8, 306 MJ/m^2).

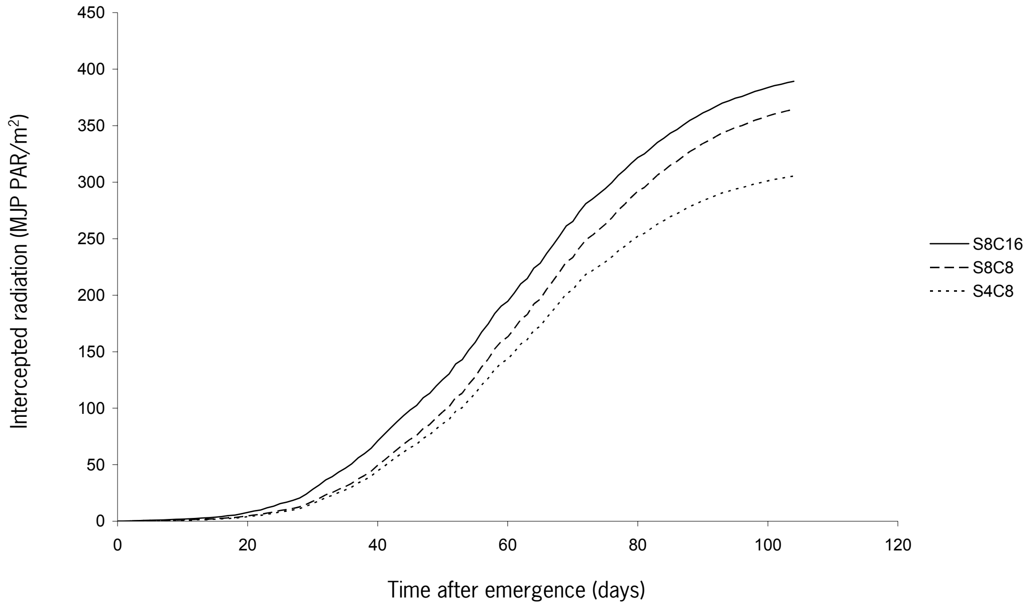

Figure 5.9. The cumulative intercepted radiation (MJ/m²) of the three intercropping systems.

LER, increase in WU and WUE

For all intercropping systems, the Land Equivalent Ratio-values of biomass and harvestable organ were higher than one and therefore the intercrops were relatively more productive than the pure stands (Figure 5.10). The LER values of the biomass were higher than for harvestable organ, because in intercropping the biomass was proportionally less decreased than the harvestable organ, which was formed at the end of the growing period when competition was higher. The LER-value increased as the intercropping density decreased. This was due to higher competition for light in the higher density intercrops and hence lowers biomass production compared to the pure stand. The contribution of sorghum to the LER was always higher than that of cowpea and was the lowest in the lowest overall density. Contribution of the sorghum was higher in the LER for harvestable organ than for biomass production.
The water use increased from pure stands; the increase of WU from the average of the pure stands (equation 2.3) was 15, 17 and 16% for S8C16, S8C8 and S4C8, respectively. The WU increased due to a shorter growth period and hence lower water use in cowpea. The increase of WUE from the average of the pure stand (equation 2.4) was 37, 49 and 45% for biomass in the S8C16, S8C8 and S4C8 intercrops, respectively. For harvestable organ, the increase in water use efficiency was 24, 36 and 35% for S8C16, S8C8 and S4C8, respectively. The increase was the lowest for the S8C16 intercrop, because water was already used more efficiently in S8 and C16 than in the lower pure stands.

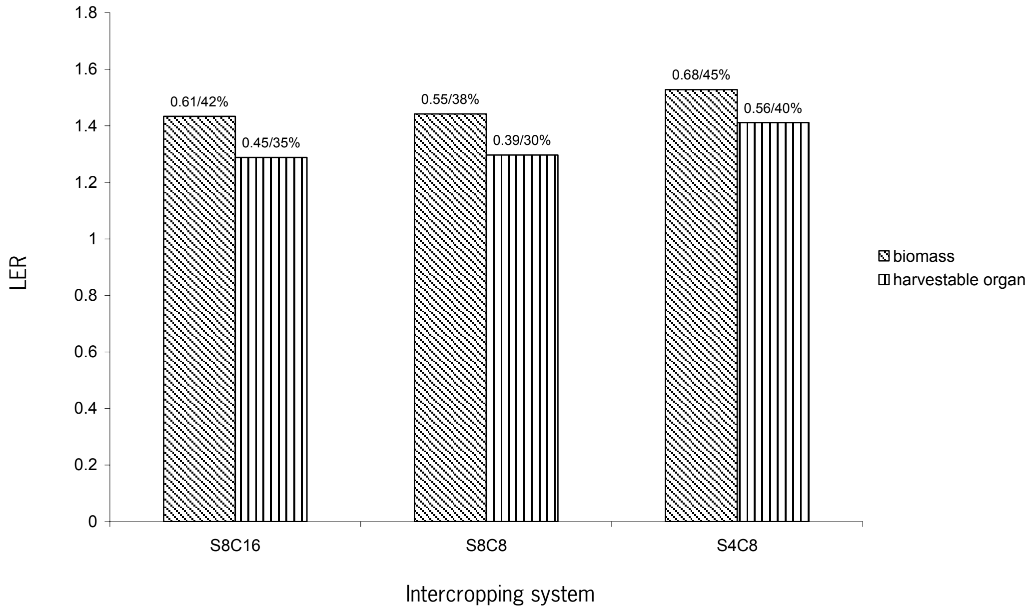

Figure 5.10. The Land Equivalent Ratio for biomass and yield for the three intercropping systems. The values above each bar are the absolute and relative contributions of cowpea to the LER.

5.2 Simulation results at various levels of water input

Biomass and harvestable organ

Decrease in water supply caused a decrease in biomass and harvestable organ production, which was most severe when water supply decreased from 50 to 25% of normal rain. For sorghum, the reduction in the harvestable organ was proportionally more than the reduction in the total biomass, because growth reduction was most severe at the end of the growing season. Consequently, the harvest index decreased from ±0.36 to ±0.31 when water supply was decreased to 25% of normal rain.

For cowpea, the reduction in growth between 100 and 25% of normal rainfall was the same for biomass and harvestable organ. Growth reduction was nearly as severe in the vegetative as in the generative phase of growth, thus resulting in the same ratio between harvestable organ and biomass. Harvest indices at 25% of normal rain were ± 0.37, which meant an increase in all intercrops compared to the same intercrops at full rain.

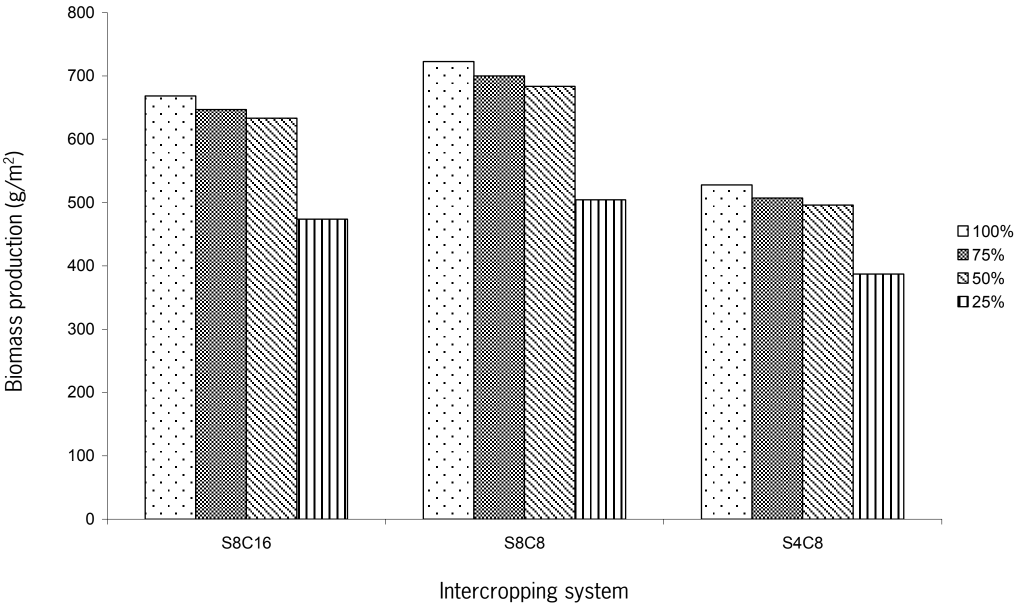

Figure 5.11. Final weight of biomass of sorghum (g/m²) in the three intercropping systems at the different amounts of rain.

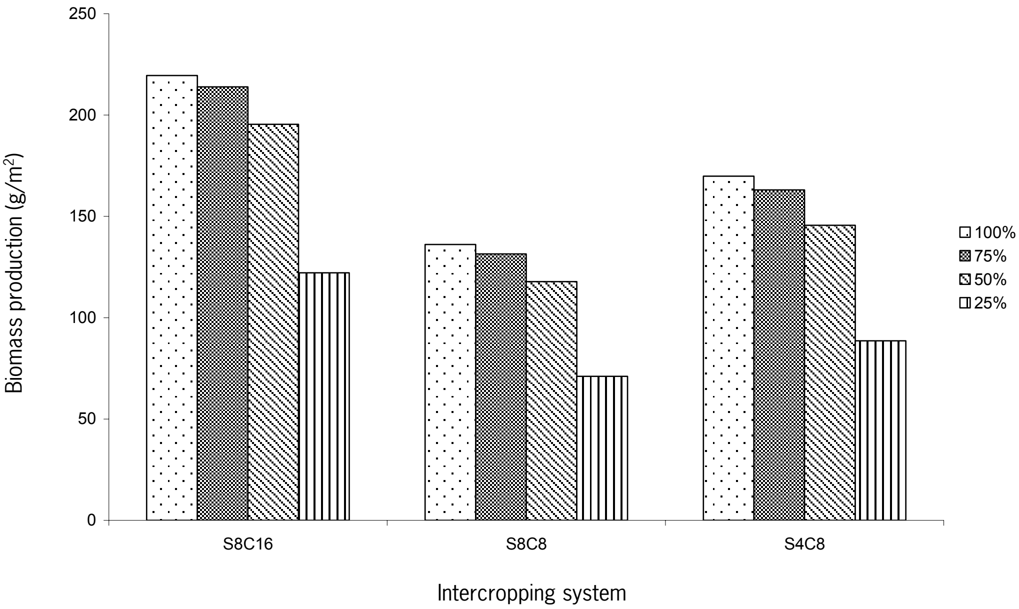

Figure 5.12. Final weight of harvestable organ (g/m²) of sorghum in the three intercropping systems at four different amounts of rain.

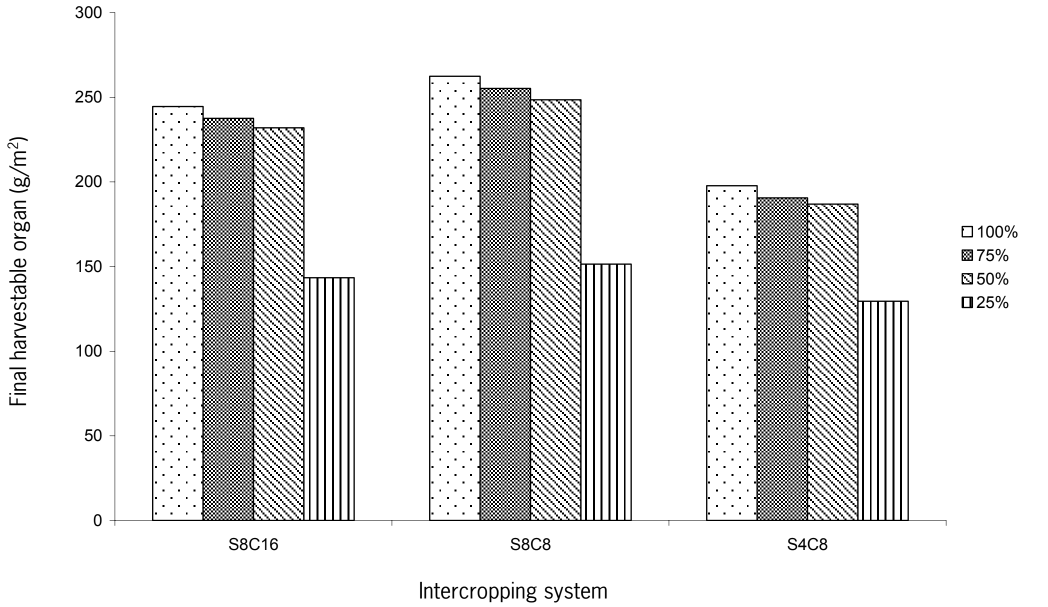

Figure 5.13. *Final weight of biomass of cowpea (g/m²) in the three intercropping systems at the different amounts of rain.*

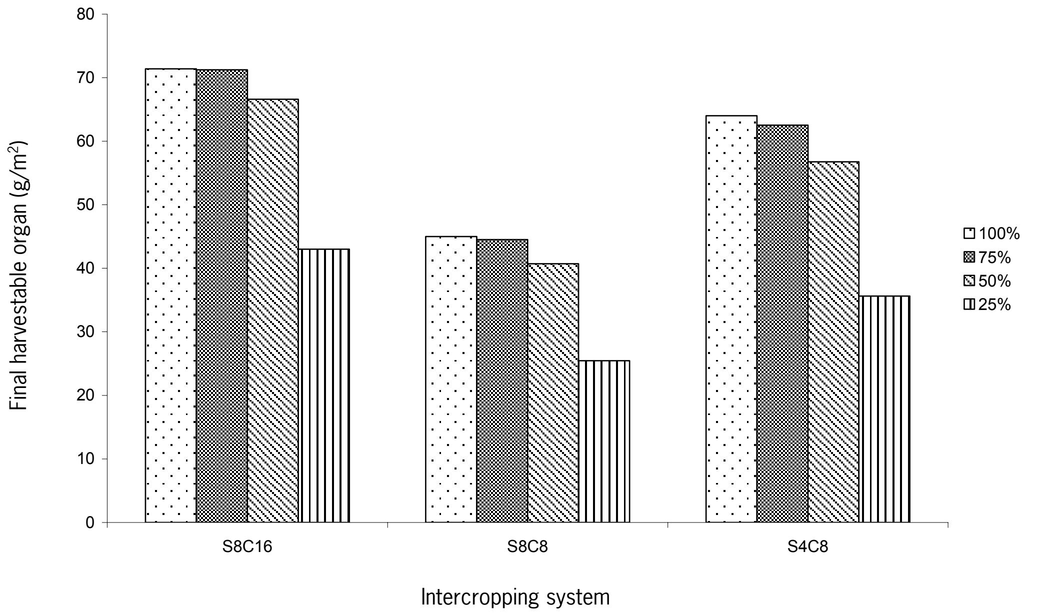

Figure 5.14. *Final weight of harvestable organ (g/m²) of cowpea in the three intercropping systems at four different amounts of rain.*

Craufurd (2000) reported that cowpea yield was only 10% of the sorghum yield. In the simulations, these percentages were higher (16-33%), depending on the density. This difference might be related to the planting time of cowpea in the experiments where this crop was planted seven days after the sorghum. Faris *et al.* (1983) obtained sorghum grain yields of 112-298 g/m^2 in well fertilized intercrops. These yields are in line with the current simulation results (130-262 g/m^2, depending on density and rainfall). In his experiment, sorghum density was slightly higher (12.5 plants/m^2 compared to 8 or 4 plants/m^2 in our simulations) and there was probably less competition from cowpea, which had a lower density (3.13 plants/m^2). The cowpea yield in his experiments ranged between 4 and 70 g/m^2 in well fertilized plots, which is in line with our results (25-71 g/m^2), but high compared to the density of his experiments (3.13 in contrast to 8 or 16 plants/m²). Rees (1986a,b) obtained grain yields of sorghum in the range between 0.6 and 38 g/m² and for cowpea between 0 and 32 g/m², which is all lower than the simulation results. The rainfall in his experiments was extremely low, comparable to the 25% level in our simulations. Morris *et al.* (1990) found sorghum yields of 70-238 g/m² at 10 plants/m² in combination with 12.5 cowpea plants/m². The simulation results are in line with these results. His cowpea yield was comparable to those from the simulation, 47-66 g/m². Lightfoot and Tayler (1987) had sorghum grain yields of 5.4-381.5 g/m² and cowpea grain yields of 2.8-53.5 g/m². The differences in yields were caused by differences in year, site and density. His highest yields were higher than the sorghum simulation results but lower for the cowpea simulation results. Gilbert (1996) obtains sorghum yields between 149-188 g/m² at a density of 5 sorghum plants/m². His cowpea yields were very low at 2-6 g/m². Both sorghum and cowpea were lower than in our simulation results, while rainfall was higher (849 mm).

Specifics of water use

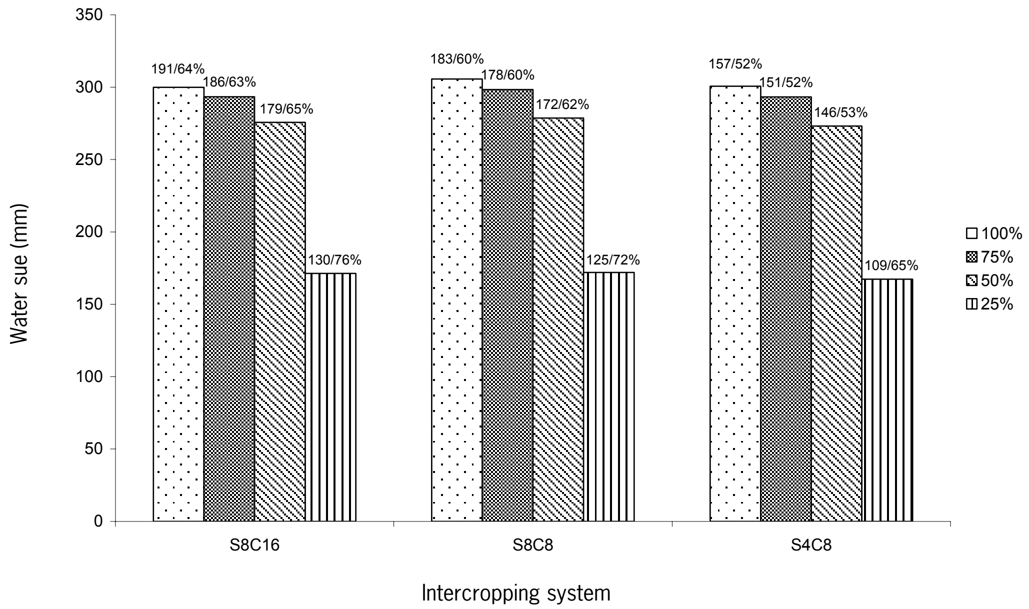

Figure 5.15. The water use (mm) of the three intercropping systems at four different levels of rainfall. Values above the bars give the absolute and relative amount of water used for transpiration.

Water use diminished as less water was added to the system. Initially, water use only diminished a little resulting from small decreases in transpiration and evaporation. A reduction in water supply from 50 to 25% caused a major reduction in water use. The water use in the different intercrops at the same level of water input was nearly the same, but amounts of water used for transpiration differed. The water used for transpiration ranged from 52 to 76%. According to Bessembinder *et al.* (2005) the percentage of transpiration is >75%. In the simulation results, it was often lower, indicating that the water was not used optimally. The water use of the sorghum-cowpea intercropping of Morris *et al.* (1990) was 336 and 432 mm in two different years. Results from the simulations were somewhat lower.

Figure 5.16 shows the distribution of the water available from rainfall between the various destinations at the end of the growth period for S8C16. As the water supply was decreased, the percolation and the change in soil water decreased first. This enabled evaporation and especially transpiration to stay at approximately the same level and thus allow nearly unrestricted growth. In relative terms, more water was used for transpiration as the water input decreased to 50%. At 25% of normal rainfall, the system used water from the buffer in the soil and the change in soil water was negative. The trends below were also seen in the other intercropping systems.

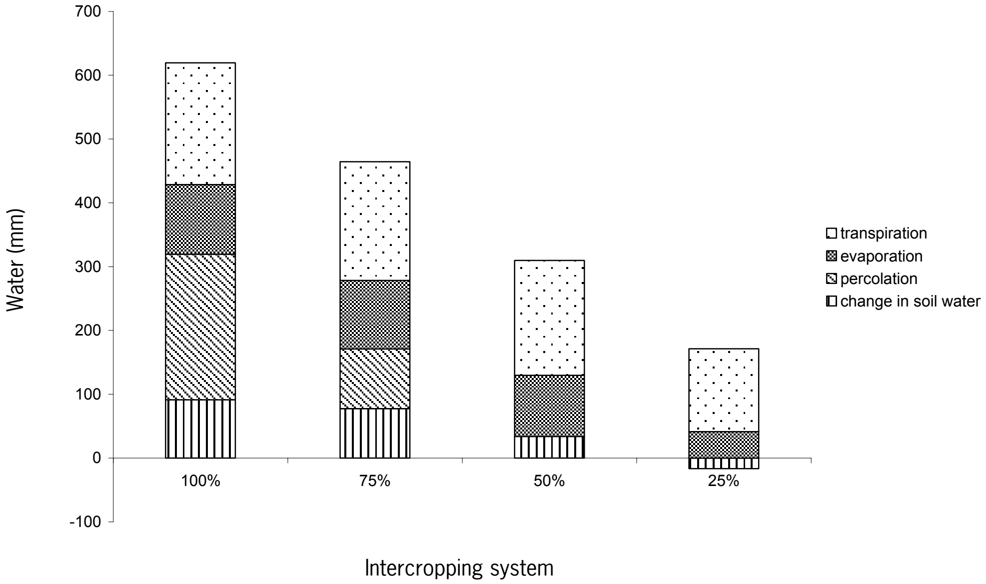

Figure 5.16. The distribution of the rainfall partitioned over a) change in soil water, b) percolation, c) transpiration and d) evaporation of the intercrop S8C16 at four different levels of rainfall.

The water use efficiency for biomass production increased when water supply decreased (Figure 5.17). Especially in the last step of diminishing water, the WUE increased, due to higher fraction transpiration in the WU. For the harvestable organ the efficiency had not a clear trend in all intercropping systems. When the cowpea density was higher than the sorghum density (S8C16 and S4C8) the WUE increased, while for S8C8 it decreased. The water use efficiency was lower when overall density of the intercrop was lower. Water use efficiencies at 100 and 75% of normal rain would even be lower when the percolated water would be incorporated in the water use. The water use efficiencies calculated from the experiments of Morris *et al.* (1990) for grain yield in the intercropping are 0.00075 and 0.00067 g dm/g water. This is lower than the simulated results, but water in the systems is only assumed to be used for evaporation and transpiration, so their WUE can be higher when percolation had occurred.

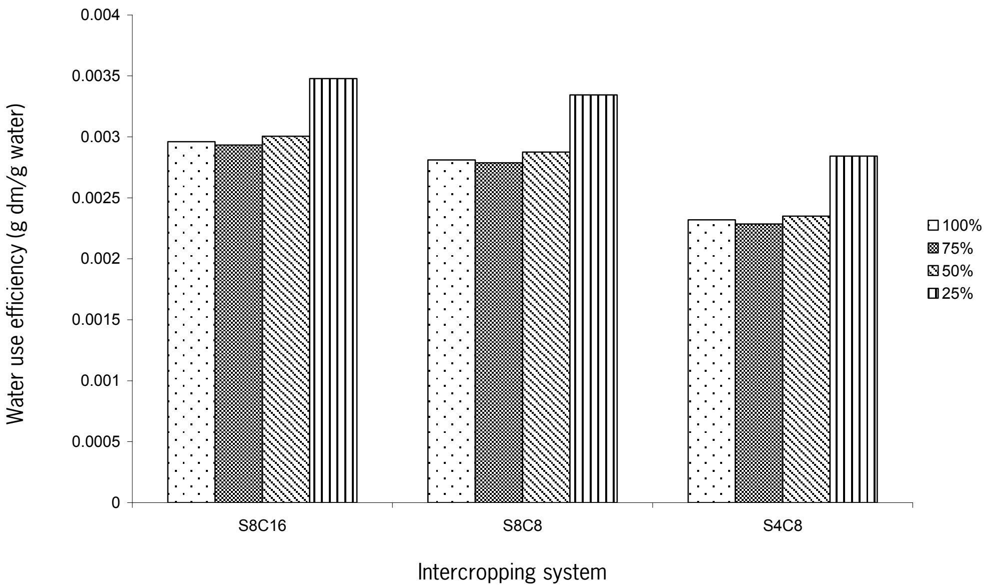

Figure 5.17. The Water Use Efficiency (g dm/g water) of the three intercropping systems at four different levels of rainfall.

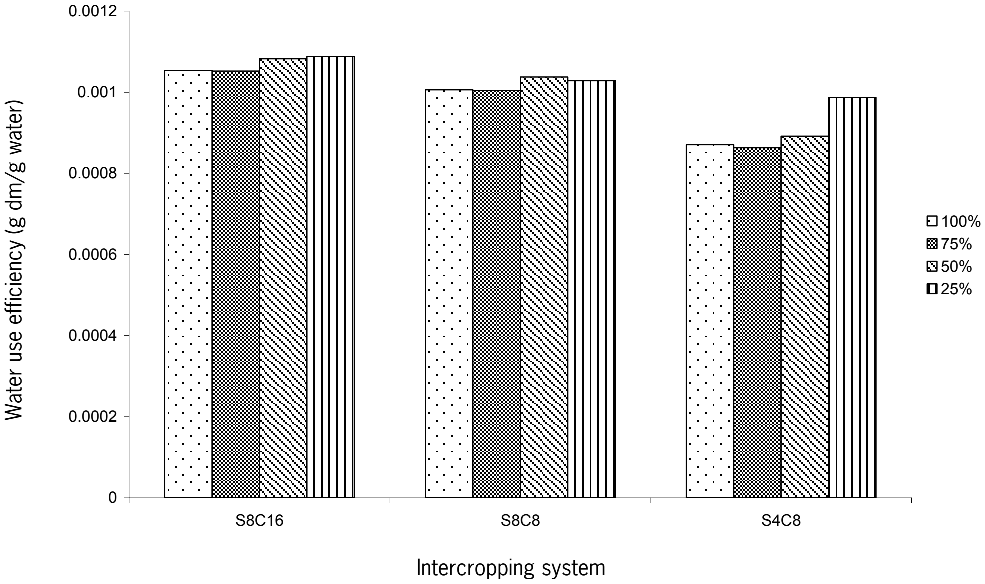

Figure 5.18. The water use efficiency for yield (g yield/g water used) of the three intercropping systems at four different levels of rainfall.

Water in soil

The time course of total soil water, plant available water for sorghum and plant available water for cowpea resembled that of the crops in monoculture and is therefore not shown.

Radiation interception

The amount of intercepted radiation was reduced when water supply was diminished, due to a lower LAI. The radiation interception was reduced with ±20% when water supplied decreased to 25%, which was lower than the reduction in biomass (± 32%). This indicates that the reduction in growth was not only due to a lower light interception but also due to additional water stress, particularly in the later growth stages. This growth reduction due to water stress decreased the effective radiation use efficiency.

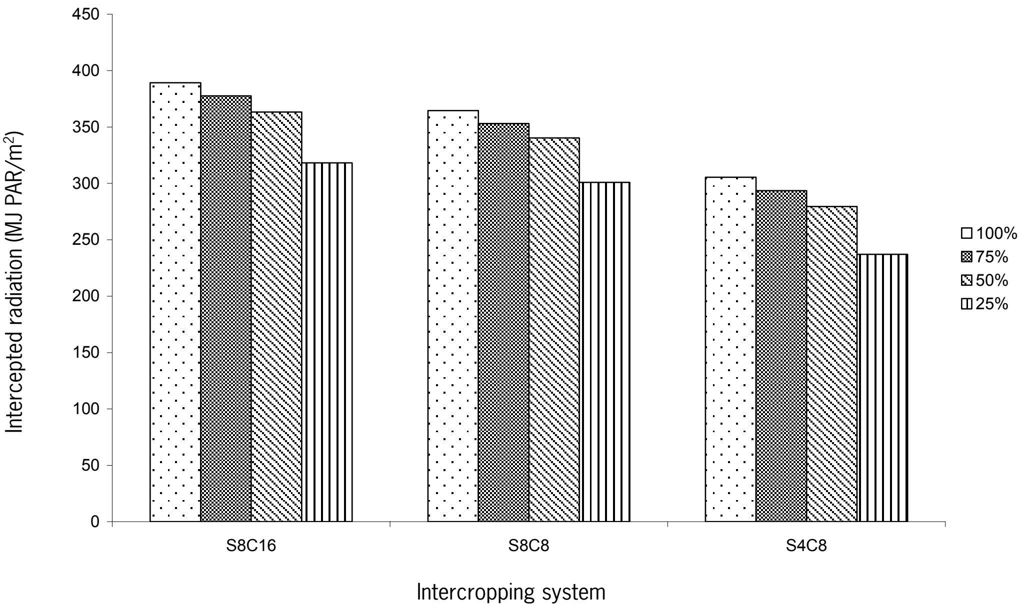

Figure 5.19. The total intercepted radiation (MJ/m^2) by the three intercropping systems at four different levels of rainfall.

LER, increase in WU and WUE

All intercropping systems at all levels of water input had a LER higher than one, so they were more productive than the pure stands (Figures 5.20 and 5.21). The LER increased with decreasing water supply. The absolute and relative contribution of the cowpea to the LER stayed approximately the same. The contribution of the cowpea was higher in the $LER_{biomass}$ than in LER_{yield}. The yield is relatively more reduced in intercrop than the biomass, because the yield is formed at the period when competition from sorghum is stronger.

The trends in the LER with decreasing rainfall can be explained by the partial LER of sorghum and cowpea, which is the comparison between the yield in intercrop and in pure stand. At low levels of water supply, biomass and yield decreased relatively more in the pure stand than in intercropping, due to heavier water stress and hence partial LER is higher.

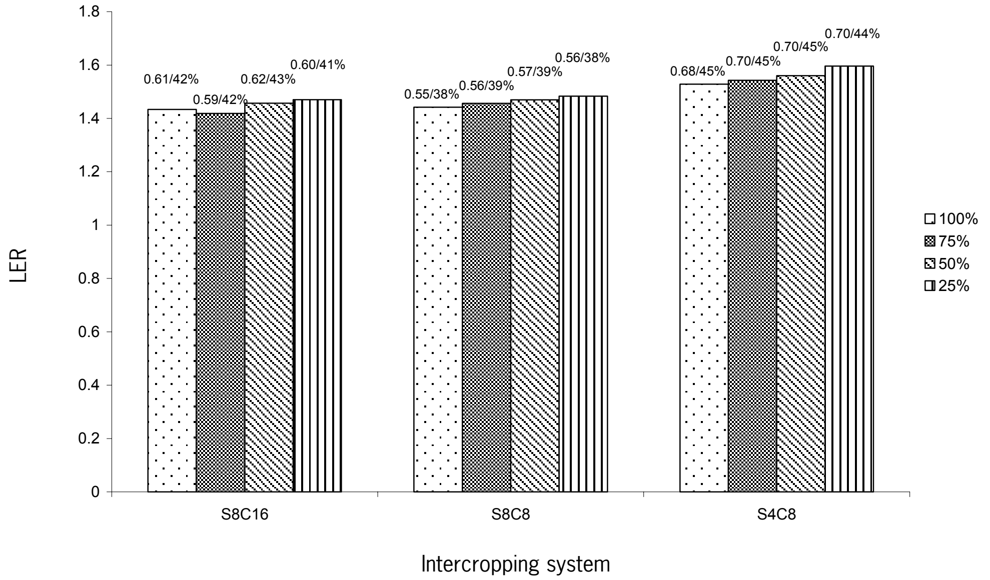

Figure 5.20. *The Land Equivalent Ratio of the biomass for the three intercropping systems S8C16, S8C8 and S4C8 at four levels of rainfall. The values above the bars are the contributions of cowpea to the LER value (absolute and relative).*

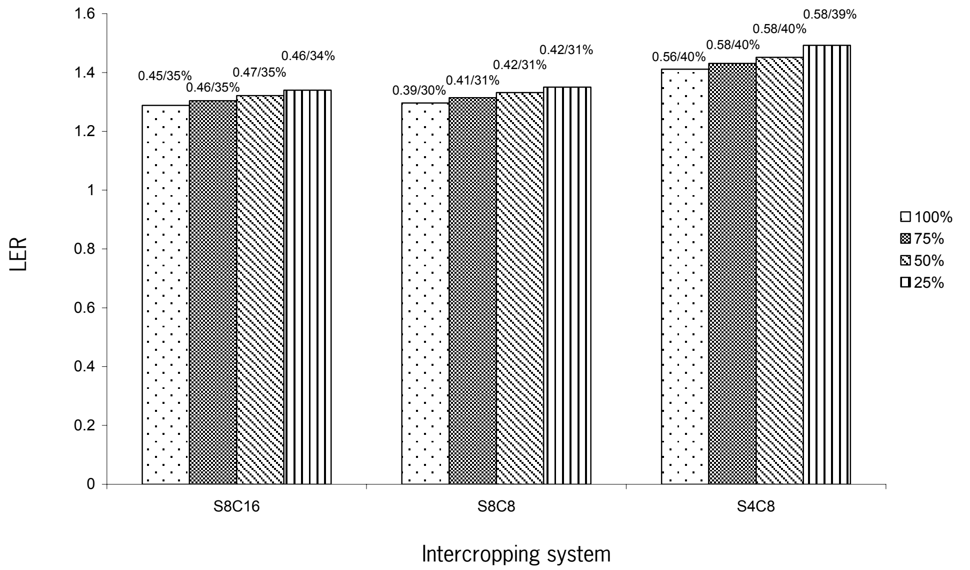

Figure 5.21. *The Land Equivalent Ratio of the harvestable organ for the three intercropping systems S8C16, S8C8 and S4C8 at four levels of rainfall. The values above the bars are the contributions of cowpea to the LER value (absolute and relative).*

Fadlalla (1999) found no increase in RYT for the biomass of a sorghum-cowpea intercrop in a pot, but the RYT for harvestable organ did increase with decreasing water supply. However, in a statistical test, there was no difference between the RYT at different levels of water supply. LER values were in generally in line with values reported in literature. Gilbert (1996) found values of 0.75-0.96. Morris *et al.* (1990) found LER values of 1.02, 1.37 and 1.65, with the highest values at the lowest amount of rainfall and the lowest value the highest amount of rainfall. Faris *et al.* (1983) found values of 0.97, 1.24, 1.42 and 1.58, depending on year and site.

The change in water use (ΔWU) and water use efficiency for biomass and harvestable organ (ΔWUE) of the intercropping systems compared to the pure stands at the same water level are found in Table 5.1.

Table 5.1. The change in water use and water use efficiency of the three intercropping systems at the four levels of water input.

intercropping system	water level (% of normal rain)	WU (% increase)	$WUE_{biomass}$ (% increase)	WUE_{yield} (% increase)
S8C16	100	15	37	24
	75	15	37	25
	50	18	37	25
	25	16	44	27
S8C8	100	17	49	36
	75	18	50	37
	50	20	51	39
	25	18	58	42
S4C8	100	16	45	35
	75	16	46	35
	50	18	47	37
	25	16	57	45

In all intercropping systems, the water use increased with respect to the pure stands when water supply was decreased from 100 till 50% of normal rain. At 25% of normal rain, the increase in water use decreased compared to 50% but was still higher than at 100 and 75% of normal rain. Morris and Garrity (1993a) calculated differences in water use between pure stands and intercrops from literature and found that there was only a difference between -6 till 7% in all intercrops and between -2 till 7% in sorghum-cowpea intercrops. Simulation results were higher, due to a shorter cowpea growing period and hence lower water use, which resulted in a low average of the pure stand. The water use efficiency increased with respect to the pure stand when water input decreased. This holds for biomass and for harvestable organ, although the advantage in the increase of water use efficiency for harvestable organ was lower. The increase was the highest at 25% of normal rainfall. At this level, the pure stands of sorghum was performing relatively bad and thus had a low WUE, while in the intercrop, the additional ground cover caused a more favourable distribution of water of transpiration and evaporation and hence increased WUE. Morris and Garrity (1993a) reported a ΔWUE of -25 till 53% for sorghum-cowpea intercrops. Our results fitted well into that range.

5.3 Input and productivity of the intercrops systems in comparison to the pure stands

The ratio of productivities of intercrops and pure stands is above one for all intercrops at all levels of water supply, this means that the absolute production of the intercrop is higher than the production of the pure stands (Figure 5.22). The ratio of biomass production of intercrops and pure stands decreased very slightly when water supply was increased. This means that the productivity in the pure stand increased proportionally more than in the intercrop. The most right point in the graph is the productivity at unlimited water supply. Also this ratio is above one, indicating at even at non-limiting water supply there is an advantage in the intercrop.

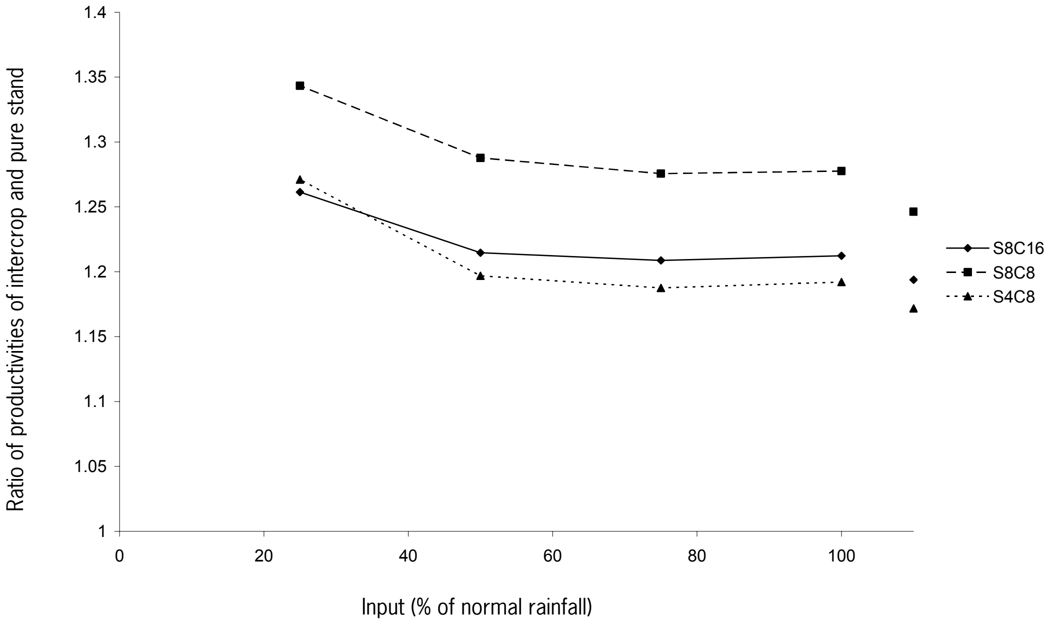

Figure 5.22. *The ratio of total biomass productivities of intercrops and their corresponding pure stands at the four levels of input used in the simulations. Single points at the right site are the situations in which water supply is non-limiting.*

Because total biomass is not the (main) scope of the farmer, the graph was also made for harvestable organ (Figure 5.23).

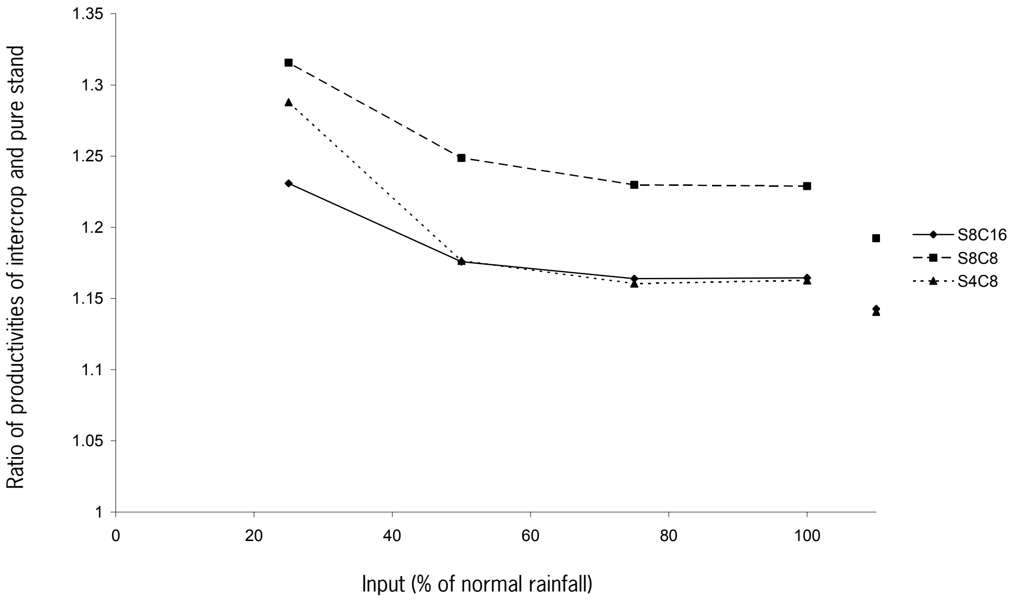

Figure 5.23. *The ratio of harvestable organ productivities of intercrops and their corresponding pure stands at the four levels of input used in the simulations. Single points at the right site are the situations in which water supply is non-limiting.*

Also for the harvestable organ, there was an advantage for the intercrop in productivity, which also exists when the water supply is non-limiting. This was also the case for the protein productivity, although the ratio came closer to one than for the other variables (Figure 5.24).

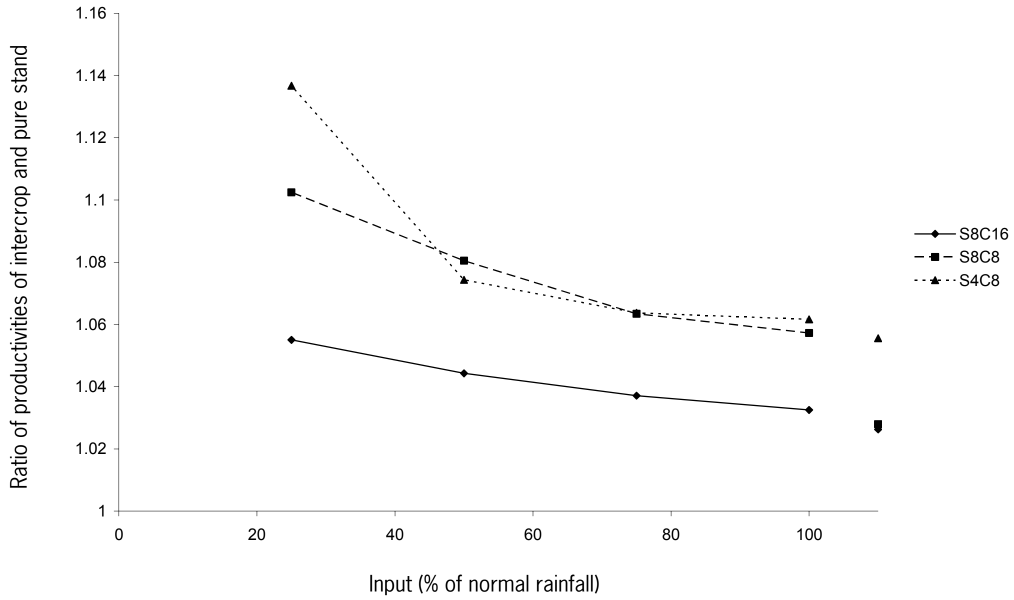

Figure 5.24. *The ratio of protein productivities of intercrops and their corresponding pure stands at the four levels of input used in the simulations. Single points at the right site are the situations in which water supply is non-limiting.*

5.4 Conclusions

In this chapter, it was shown that cultivation of intercropping systems had an advantage over pure stands at all densities. Adding cowpea to sorghum posed a restriction on growth, the severeness of the restriction was determined by the cowpea as well as the sorghum density. Total productivity was higher than in the pure stand, as were the water use and the water use efficiency. Water use was nearly same for all systems, while the water use efficiency was the highest at the highest density intercrop. Compared to the pure stands, evaporation was diminished, due to a higher LAI throughout the growing season.

When water input was decreased, a reduction in biomass and yield occurred. Percolation and change in soil water decreased much more than transpiration and evaporation, resulting in a more efficient cropping system at lower levels of water supply. At 25% of rain, the water use efficiency was the highest, due to a high proportion of transpiration in the evapotranspiration. Absolute production however was quite low. The LER was higher than one for all simulations and it increased when amount of water supply decreased. This indicates a higher advantage of the intercrop over the pure stand in lower input situations. The ratio of the total productivity of intercrops and pure stands showed a slight increase with decreasing water supply. Calculation of the LER and ratio of productivity at non-limiting water supply showed that also then the intercrop had an advantage over the pure stand.

6. Results and analysis of the model simulations III: improving productivity by manipulating plant parameters or agronomic practices

In this chapter, possible changes in plant traits or agronomic practices on the productivity of the intercrops were tested. Numerical results of the simulations are found in Appendix IV.

6.1 Plant traits

Decreasing sorghum height

As sorghum height decreased, sorghum yield in intercropping decreased with respect to the original simulations. Cowpea yields increased as the sorghum height was decreased (compare Figures 6.1 and 6.2 with Figures 5.12 and 5.14). The trends in the sorghum and cowpea yield at different amounts of rain were the same as in the original simulations. The total productivity of harvestable organ decreased compared to the original simulations.
The decrease in yield of sorghum and increase in yield of cowpea was according to the expectations. Sorghum intercepted less light, whereas light interception of cowpea increased. The LUE of cowpea was lower than for sorghum, so the decrease in sorghum harvest was not completely compensated by the increase in cowpea harvest and consequently the total productivity of harvestable organ was lower. For the same reason, also the LAI was lower. This resulted in lower transpiration and hence, no additional growth reduction occurred compared to the original simulations.
Changes in pure stands didn't occur, since height is only important in competition.

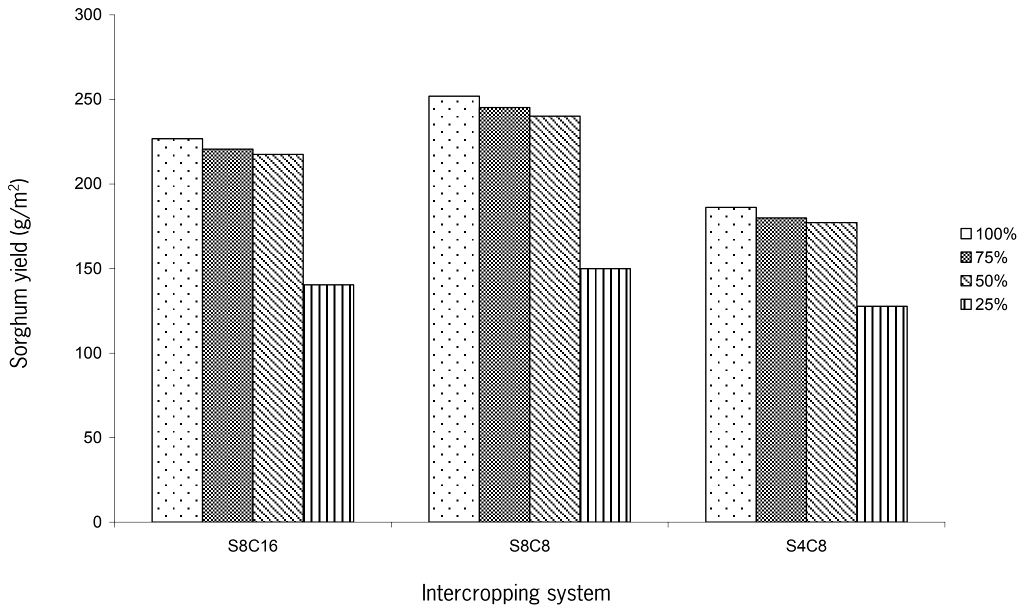

Figure 6.1. The final weight of the harvestable organ of sorghum in intercropping (g/m^2) when the sorghum height was decreased from 2 to 1.5 m.

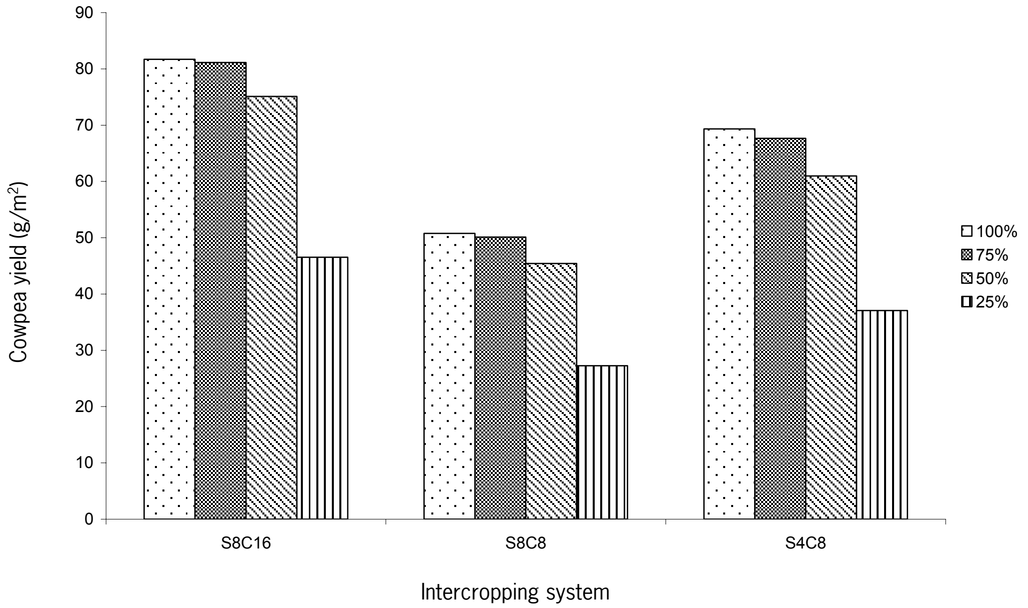

Figure 6.2. *The final weight of the harvestable organ of cowpea in intercropping (g/m²) when the sorghum height was decreased from 2 to 1.5 m.*

Figures 6.3 and 6.4 show the LER of the harvestable organ and the ratio of productivity of the harvestable organ and proteins of intercrops and pure stands.

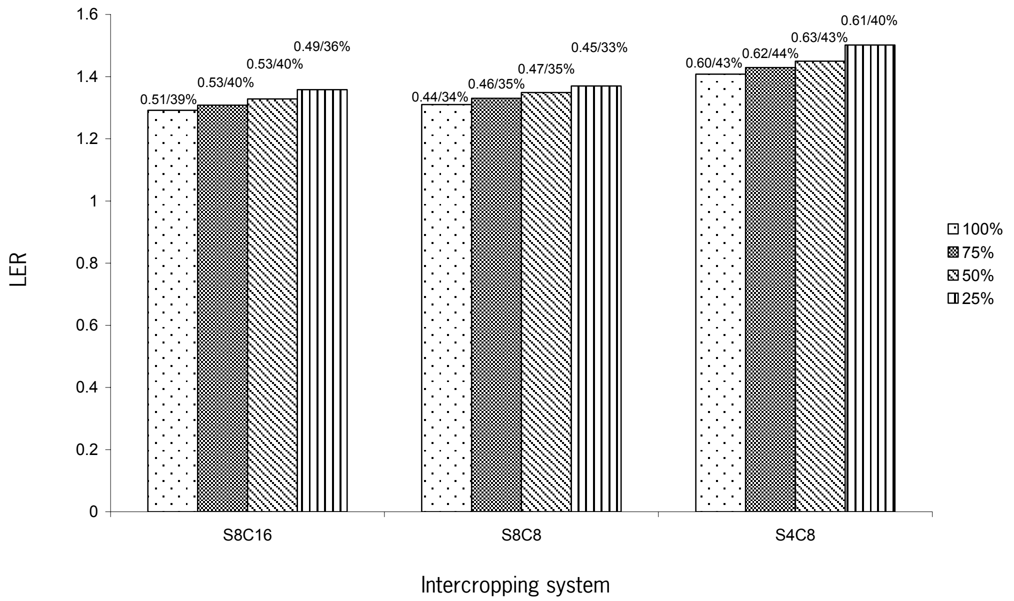

Figure 6.3. *The Land Equivalent Ratio of the harvestable organ of the three intercropping systems when the maximum height of sorghum was decreased from 2 to 1.5 meter.*

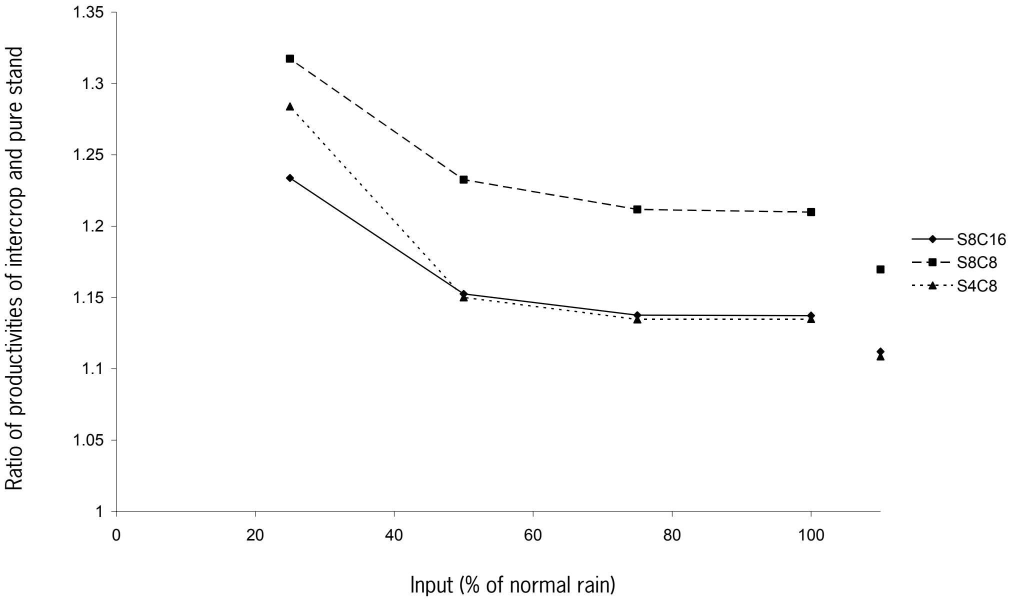

Figure 6.4. *The ratio of productivities of the harvestable organ (filled symbols) and protein yield (open symbols) of intercrop and pure stand at the four levels of input used in the simulations. Single points at the right site are the situations in which water supply is non-limiting.*

The LER values of all intercrops showed the same trend as in the reference simulations. The absolute and relative contributions of cowpea to the LER increased at the cost of the contribution of sorghum. The values of the LER's were slightly higher than the reference simulations.

With respect to the trends in the ratio of productivity, the results were comparable to the ones from the original simulations for the harvestable organ. The ratio at unlimited water supply was also included and showed that even at unlimited water supply, there was an advantage of the intercrop over the pure stand. The ratio was higher than in the reference simulations at the low water input, but lower at high water input.

Increasing the light use efficiency of cowpea

When the LUE of cowpea would be 2.0 g/MJ instead of 1.8 g/MJ, the intercrops would have the following results for the harvestable organ (Figures 6.4 and 6.5).

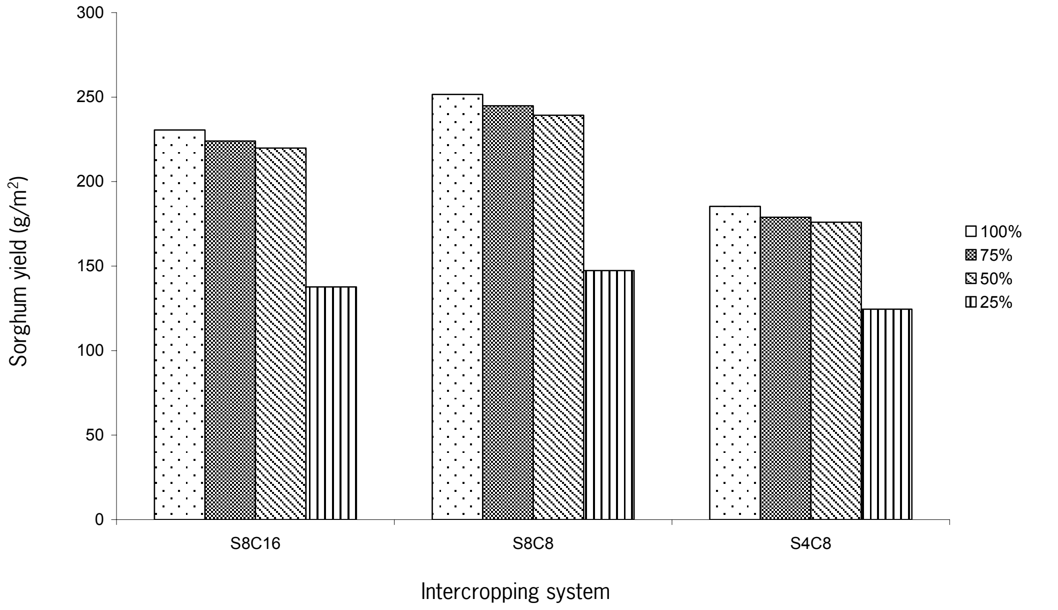

Figure 6.5. *The final weight of the harvestable organ of sorghum in intercropping (g/m²) when the cowpea had a light use efficiency of 2.0 g/MJ.*

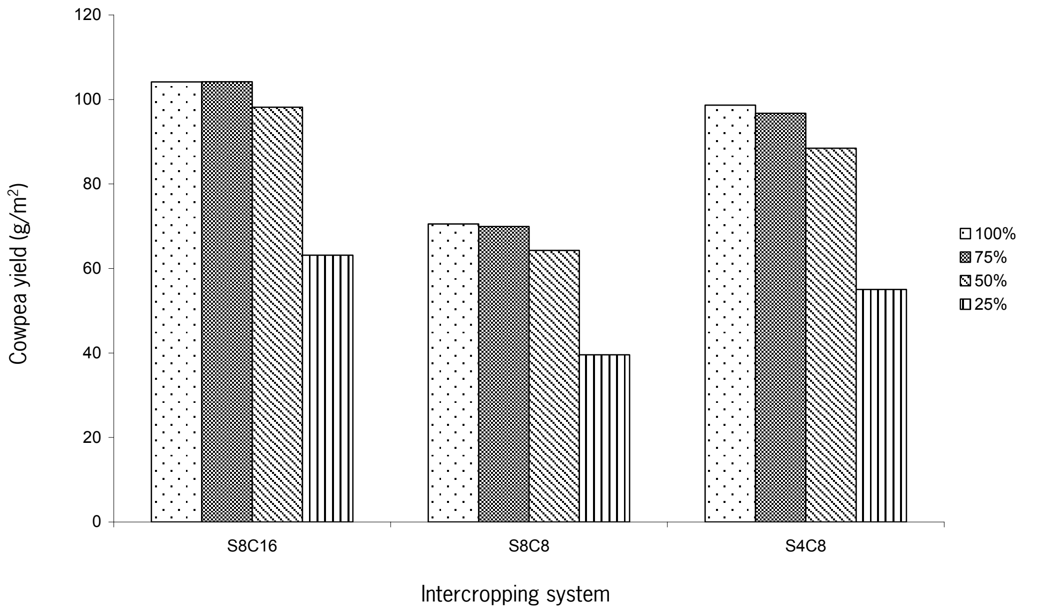

Figure 6.6. *The final weight of the harvestable organ of cowpea in intercropping (g/m²) when the cowpea had a light use efficiency of 2.0 g/MJ.*

The trend of the final weight of the harvestable organ of sorghum and cowpea with decreasing water supply was the same as in the original intercrops. The final values for sorghum were slightly lower, while those for cowpea were 150% higher. Overall production had thus increased. This was according to the expectations. Through increasing the LUE of cowpea, its leaf area increased and cowpea became a better competitor for light in the lower layer. Sorghum therefore lost some weight at the expense of cowpea.

Yields for cowpea in the pure stands were of course higher than in the original stands (varying between +35% and +51% when rain decreased from 100 to 25%) and hence overall productivity in pure stand increased.

The LER for harvestable organ is shown in Figure 6.7, while the ratio of harvestable organs and protein yields of intercropping and pure stands are shown in Figure 6.8.

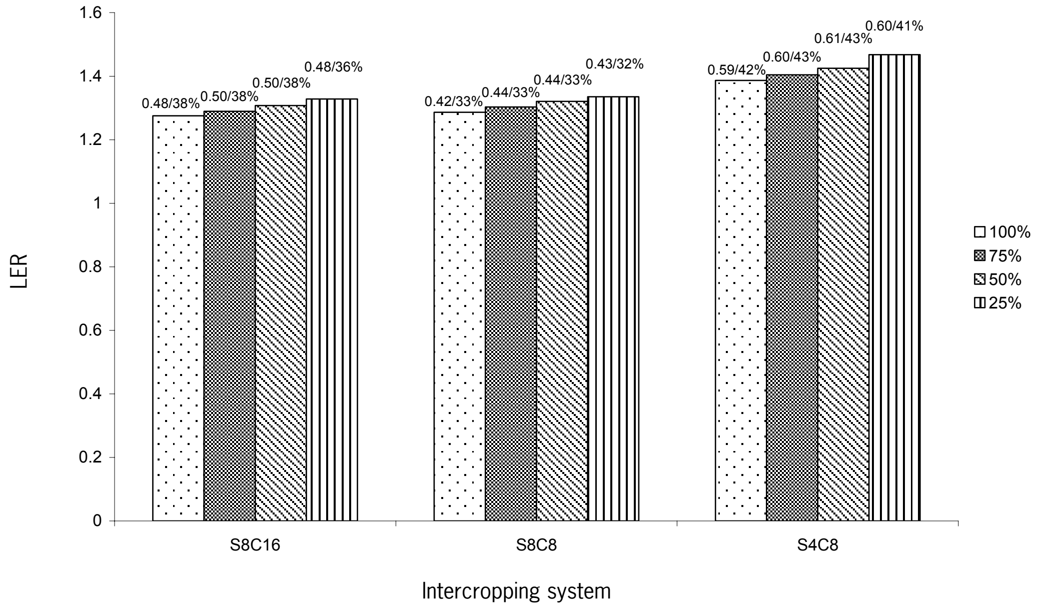

Figure 6.7. *The Land Equivalent Ratio of the harvestable organ of the three intercropping systems when the light use efficiency of cowpea was increased from 1.8 to 2.0 g/MJ PAR.*

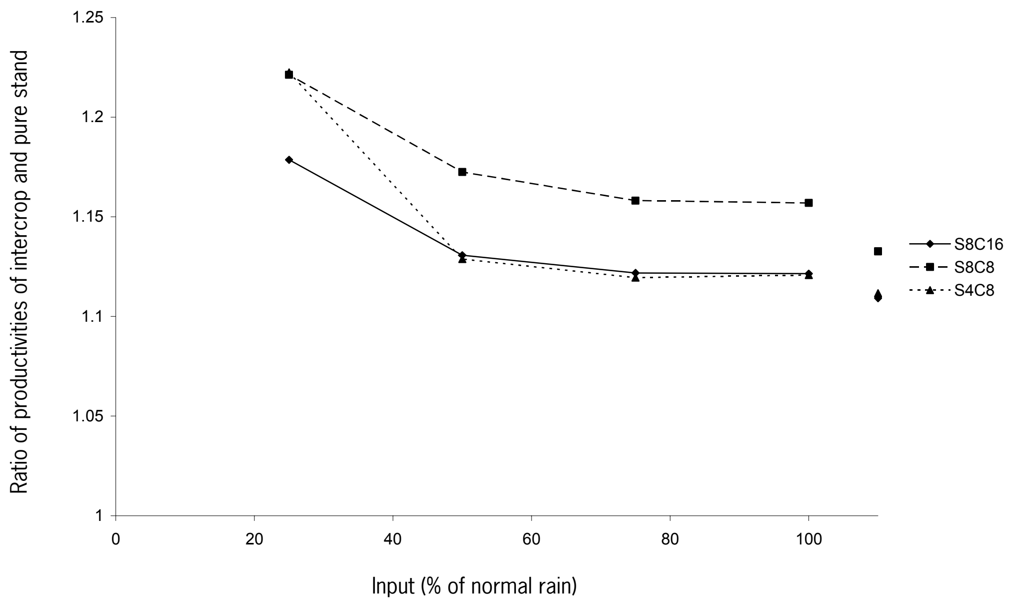

Figure 6.8. *The ratio of productivities of harvestable organ (full symbols) and proteins (open symbols) of intercrops and pure stand at the four levels of input used in the simulations, when cowpea had a light use efficiency of 2.0 g/MJ. Single points at the right site are the situations in which water supply is non-limiting.*

The LER in all intercropping systems showed an increase when the water supply decreased. The values of LER had slightly decreased from the reference simulation results. The absolute and relative contribution of cowpea to the LER increased slightly. Sorghum performed relatively worse compared to the pure stand, which caused the decreasing in partial LER of sorghum and also a decrease in the total LER.

The ratio of productivity of the harvestable organ decreased with increasing water supply. The ratios were lower compared to the original simulations, but still higher than one. Also for unlimited growth, the ratio is higher than one.

6.2 Agronomic practices

Later planting of sorghum

Figures 6.10 and 6.11 show the harvest of sorghum and cowpea in intercropping if sorghum emerged one week later than cowpea (day 192 instead of day 185).

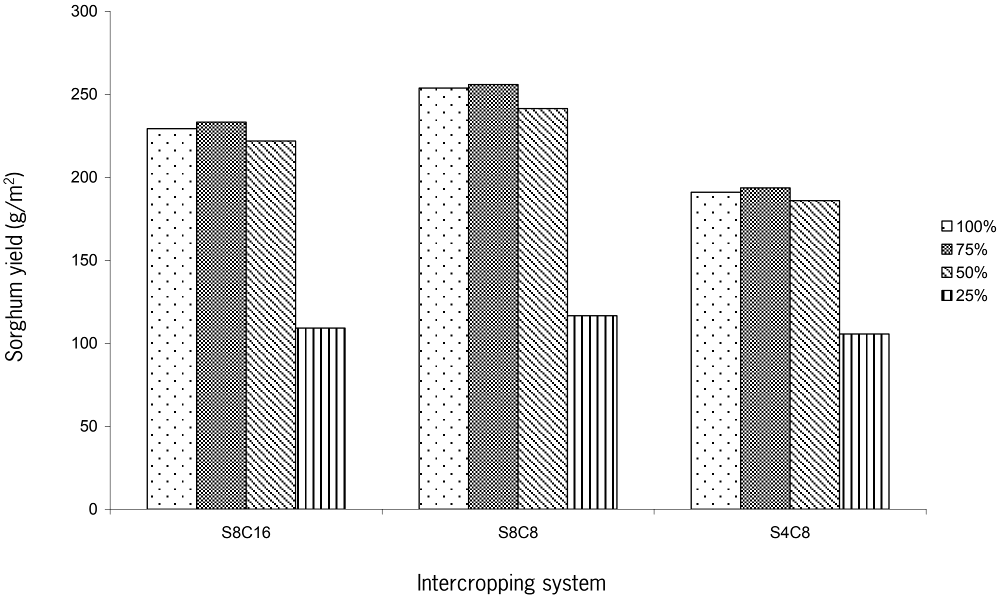

Figure 6.9. The final weight of the harvestable organ of sorghum in intercropping (g/m^2) when the sorghum emerged one week later.

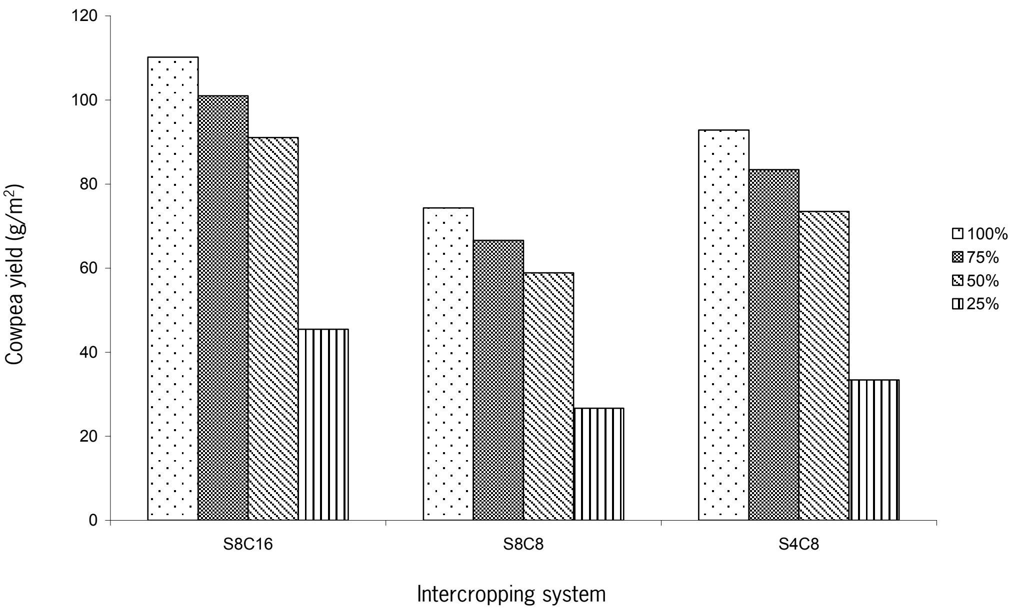

Figure 6.10. The final weight of the harvestable organ of cowpea in intercropping (g/m^2) when the sorghum emerged one week later.

In the intercrop, sorghum yield was not the highest at 100% of normal rainfall but at 75%. This is due to heavier growth reduction in cowpea in 75% of rainfall during the vegetative phase, which left more light for the sorghum and thus increases its yield. At lower levels of water input, the yield showed a decrease. The cowpea yield was continuously decreasing with decreasing water supply. Compared to the reference simulations, sorghum yield was lower, due to higher competition from cowpea and the additional water stress. Cowpea had a higher yield, due to a better competitive position. The total productivity in the intercropping was higher than in the reference simulations at 100% of normal rainfall, but lower at 25%.
The yields for sorghum in the pure stands were slightly higher than in the original simulations at high levels of water input (± 10 g/m^2 at 100% and 1 g/m^2 at 50%), but lower at the lowest water supply level.
The LER and ratio of productivities showed the following trend (Figures 6.11 and 6.12).

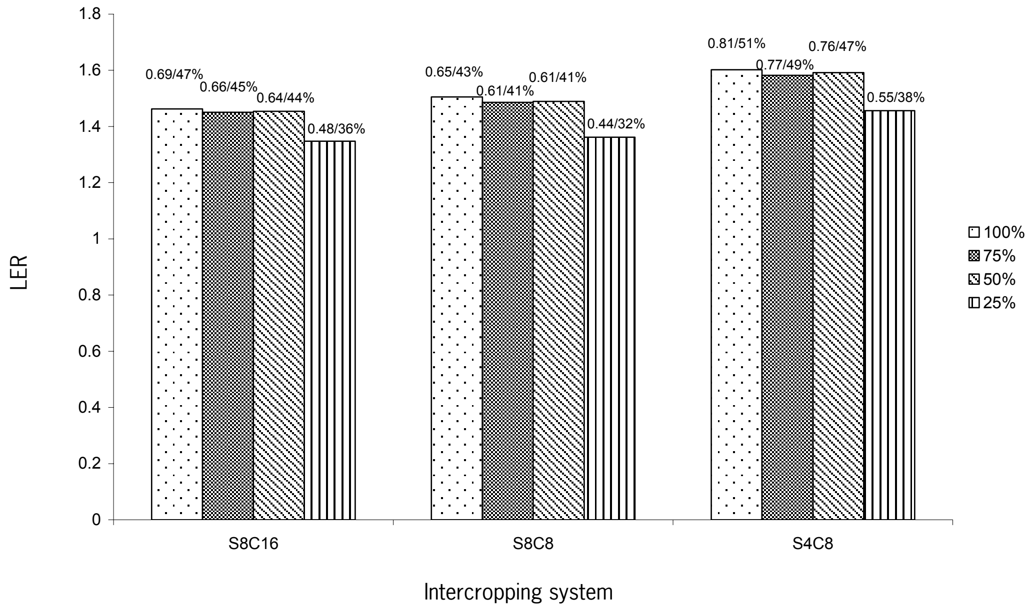

Figure 6.11. The Land Equivalent Ratio of the harvestable organ of the three intercropping systems when sorghum was planted one week later than cowpea.

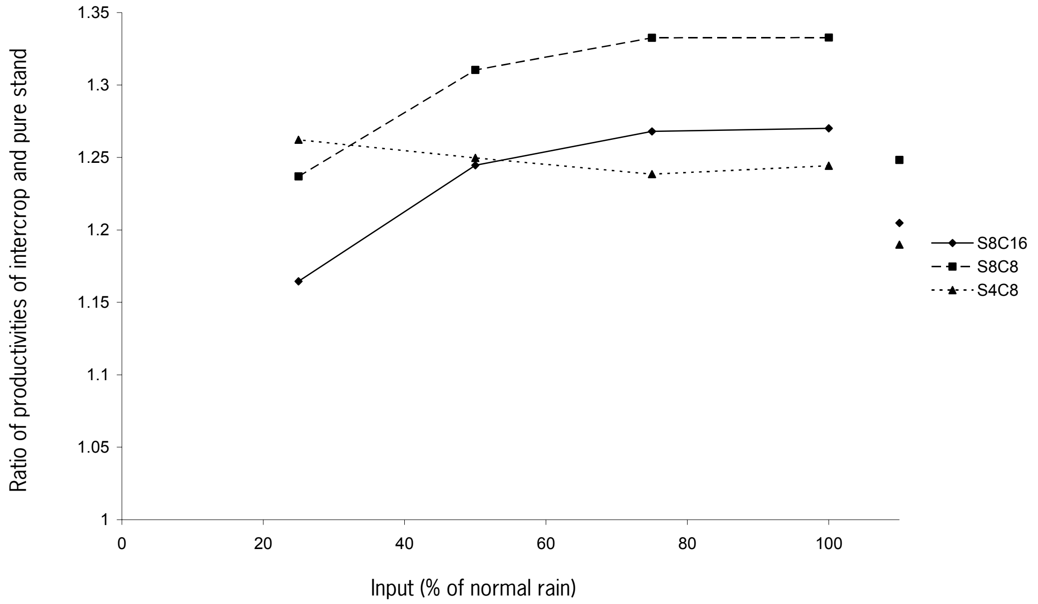

Figure 6.12. The ratio of productivities of harvestable organ (full symbols) and proteins (open symbols) of intercrops and pure stand at the four levels of input used in the simulations, when sorghum emerged one week later than cowpea. Single points at the right site are the situations in which water supply is non-limiting.

The LER-values of each intercropping system showed a decreasing trend with a decrease in water supply. This is due to a relatively worse performance of the cowpea in the intercrop at lower water supply levels and thus a decrease in cowpea partial LER, while sorghum partial LER increased. However, the total LER is higher than in the reference situations. This practice is thus only advisable in years with sufficient rainfall.
All simulations also showed an increase in the ratio of the productivities of intercrops and pure stand for harvestable organ. At low rainfall, the intercropping was performing relatively bad and for that reason the ratio was lower than at the higher water supply levels. At unlimited water supply, the ratio is still higher than one and higher than in the reference simulations.

Increasing the density

If the density of sorghum and cowpea would be increased so that the densities of the intercrops would be S16C32 and S24C32, this would result in the final weights of the harvestable organ in the intercropping presented in Figures 6.13 and 6.14.
The trend in the final weight was the same for the new density intercrops S24C32 and S16C32 as for the reference intercropping S8C16. The final values for sorghum were higher than in the reference intercropping, while for cowpea, they were lower. So, when the density of both crops was doubled (as in S16C32 with respect to S8C16), only the yield of sorghum increased, while the yield of cowpea decreased, despite a higher density than in the reference intercropping. Cowpea developed a good canopy, but during pod filling of cowpea, the LAI of sorghum was so high that pod filling was far from optimal. In this case, planting the cowpea before the sorghum would probably be a better option. In S24C32, the density of the sorghum was proportionally higher than the density of the cowpea compared to S8C16 and S16C32. The sorghum yield was higher than in S16C32, because of more sorghum plants, while the cowpea yield was lower than in S16C32, due to more competition from the sorghum plants. At 75% of rainfall, a growth reduction occurred in sorghum was increased the yield in cowpea.
In pure stands, all yields of the higher densities (S16, S24 and C32) were higher than the corresponding yields obtained at S8 or C16 at the same level of rainfall, but yield per plant decreased.

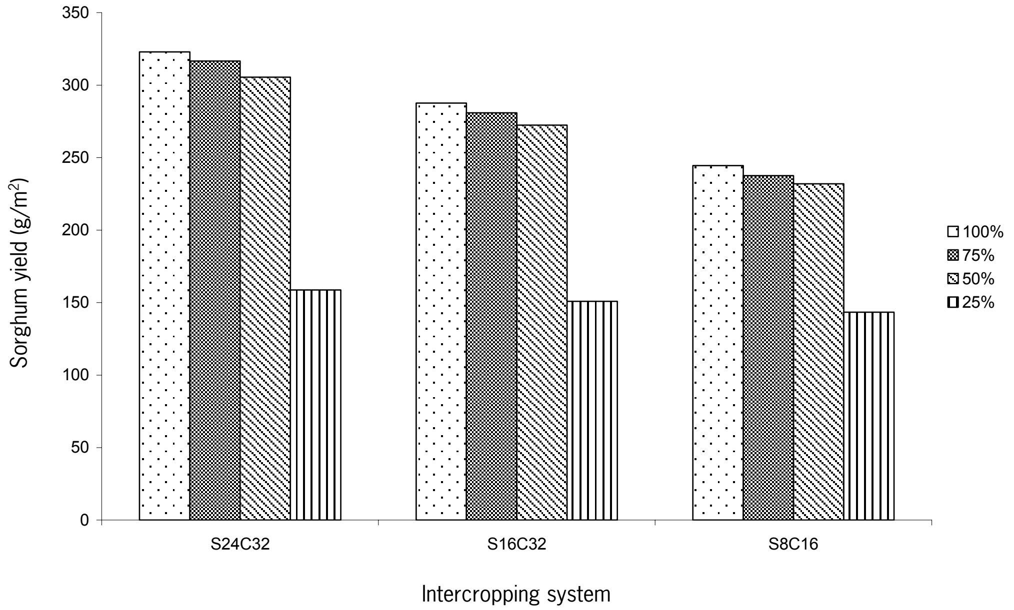

Figure 6.13. The final weight of the harvestable organ of sorghum in intercropping (g/m²) when the density was increased. The results of S8C16 are added as a reference.

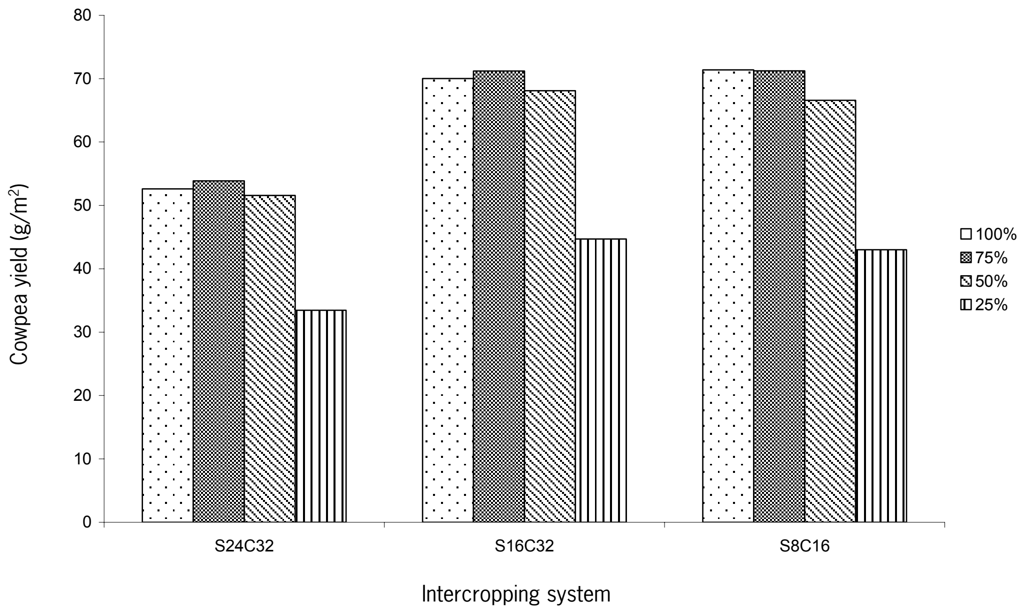

Figure 6.14. The final weight of the harvestable organ of cowpea in intercropping (g/m²) when the density was increased. The results of S8C16 are added as a reference.

The LER and difference in productivity for these simulations are shown in Figures 6.15 and 6.16, respectively.

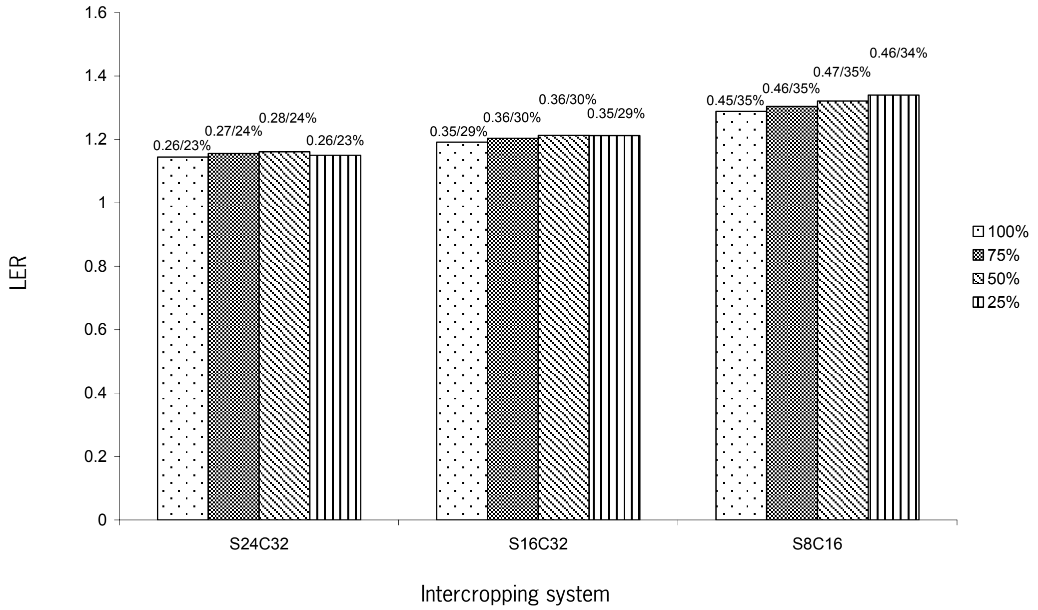

Figure 6.15. The Land Equivalent Ratio of the harvestable organ of the three intercropping systems when density was increased.

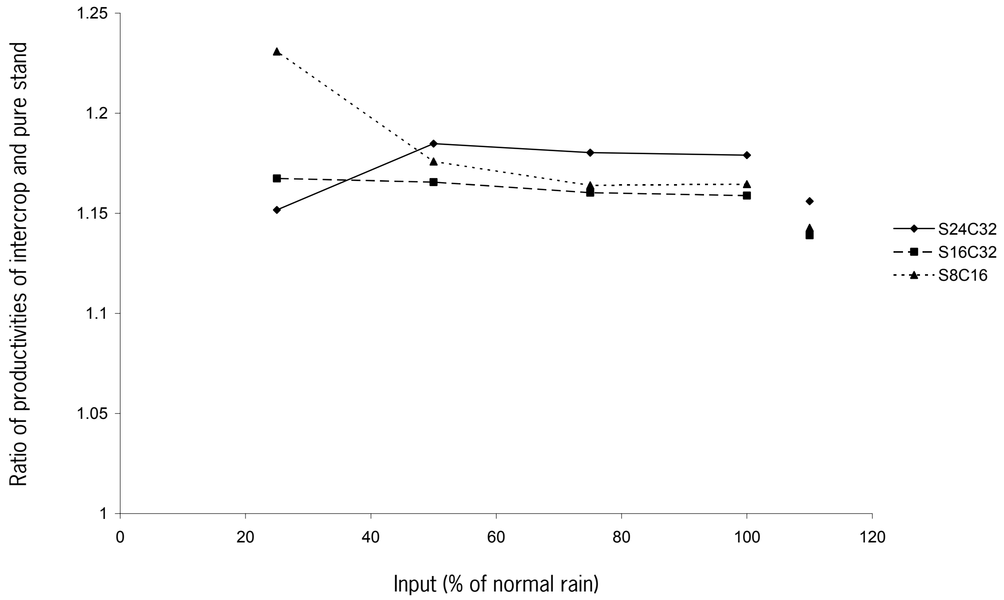

Figure 6.16. The ratio of productivities of harvestable organ (full symbols) and proteins (open symbols) of intercrops and pure stand at the four levels of input used in the simulations, when higher densities of intercrops were used. Single points at the right site are the situations in which water supply is non-limiting.

When the density was increased, the LER-values had an increasing trend with decreasing water supply, but the increase was lower than in the reference situations. Increase of the density caused a decrease of the LER-values with respect to the reference simulations of S8C16 at all levels of water supply. This is mainly due to a lower partial LER of cowpea, the partial LER of sorghum is nearly the same.

When the ratio of productivities of the harvestable organ was considered, the ratios were not continuously decreasing, but had an increase from 25% to 50% and were higher than one. So at higher densities, the extra water which became available through the increase in water supply between 25 and 50% caused a proportionally higher increase of productivity in an intercrop than in the pure stand. The ratio became also closer to one as the density increased. In general, the ratios were lower than in the reference simulations.

Evenly distributed water supply

Figures 6.16 and 6.17 show the final weights of the harvestable organ of sorghum and cowpea in intercropping, when the amount of rain would be evenly distributed over the whole period (i.e. the total rainfall of 619 mm over the growing season was evenly divided over the 105 days of the growing period).

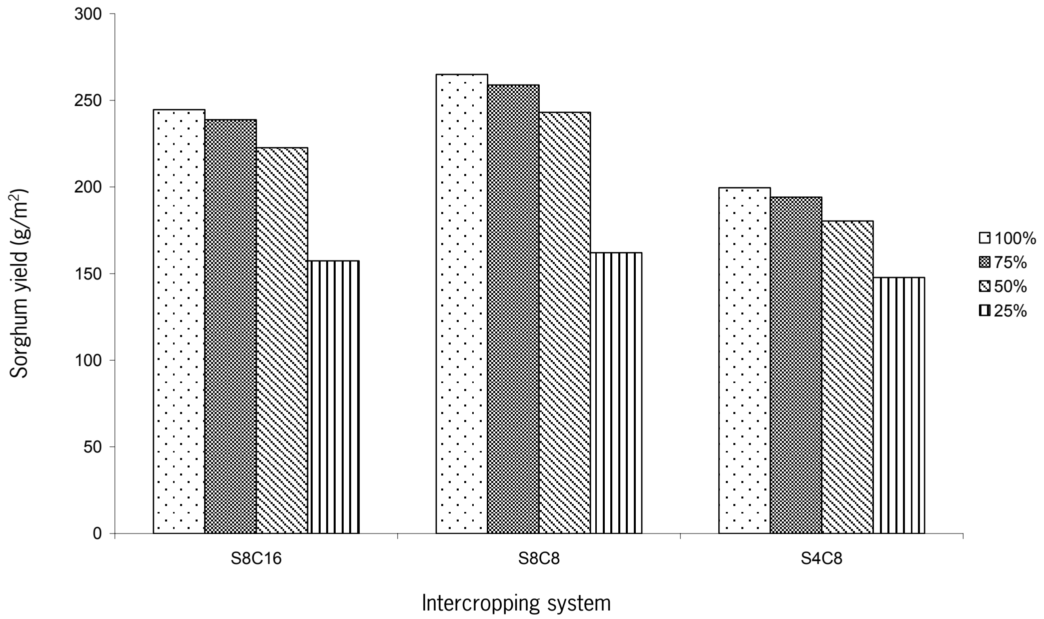

Figure 6.17. The final weight of the harvestable organ of sorghum in intercropping (g/m²) when the rain would be evenly distributed over the growing period.

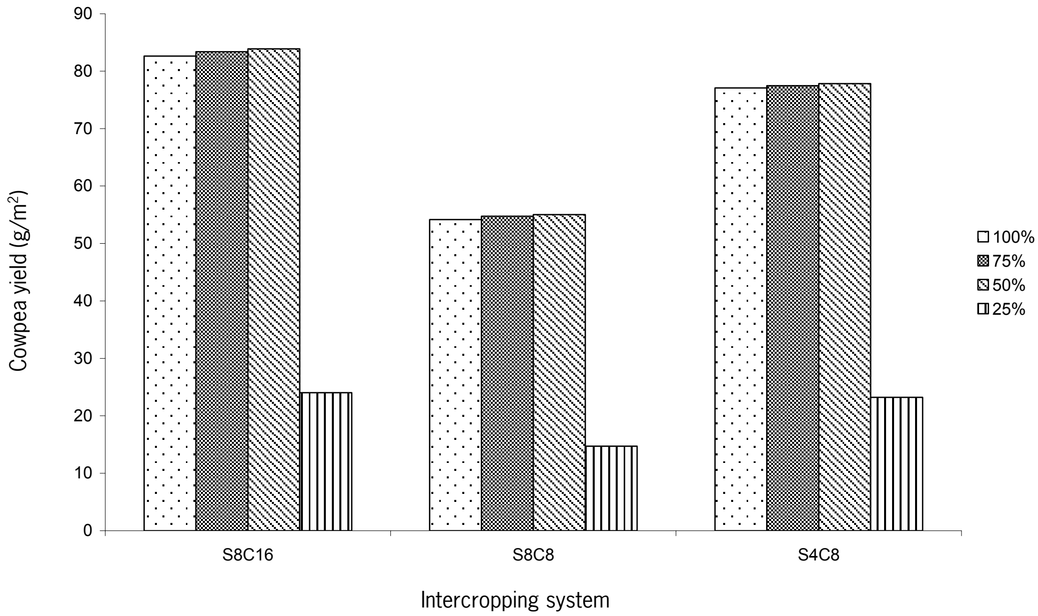

Figure 6.18. The final weight of the harvestable organ of cowpea in intercropping (g/m²) when the rain would be evenly distributed over the growing period.

Sorghum yields were approximately the same at the higher water supply levels, but lower at 50% and higher at 25% of normal rain. The former was due to some water stress around the day 66-92. Cowpea yields were higher than in the reference simulations at the first three levels of rainfall due to water stress in sorghum. At 25% of normal rain cowpea yield was lower than in the reference simulations, due to water shortage during the whole growing period, therefore benefiting the sorghum harvest. The total productivity of harvestable organ was higher compared to the reference simulations.

For the pure stands, yields were the higher than the original simulations for sorghum, but lower at 25% of normal rain for cowpea. Apparently, the timing of rainfall now suited the water demand of cowpea less than in the original simulations at 25% of normal rain.

The LER values had a small optimum at 75% of water supply. The absolute LER-values were lower than in the original simulations. The contribution of cowpea was especially lower at 25% of normal rain than in the reference situations, due relatively worse performance of the intercrop. Sorghum was performing much better than in the pure stand at 25% of normal rain, but couldn't compensate the decrease in partial LER of cowpea. In the normal simulations, the majority of the rain fell at the beginning of the growth season, causing a water shortage in sorghum at the end of the growth season. When rain is more evenly distributed, this growth reduction is less severe.

The ratio of productivities decreased with increasing water supply in all simulations, so with an increase in water supply, the pure stands were behaving proportionally better than the pure stands. The values of the ratio of productivity were comparable to the original simulations, but was higher at 25% of normal rain.

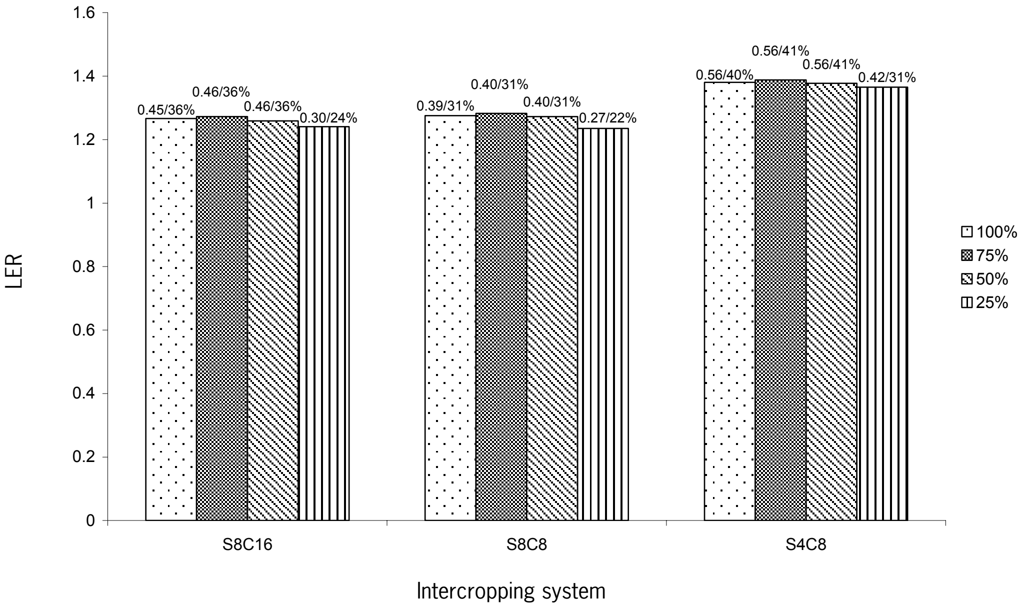

Figure 6.19. The Land Equivalent Ratio of the harvestable organ of the three intercropping systems when water supply was evenly distributed over the growing period.

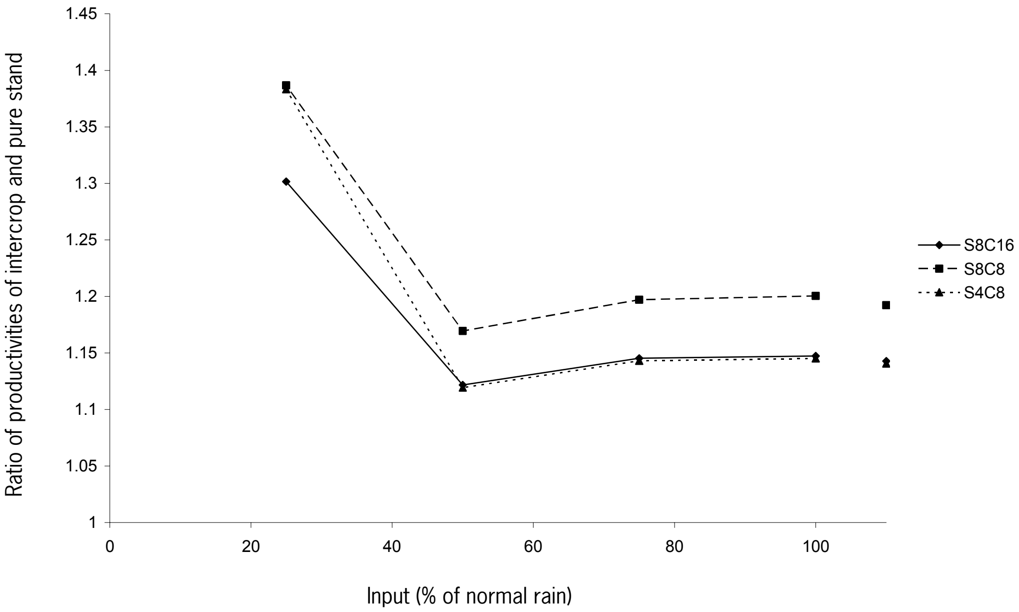

Figure 6.20. The ratio of productivity of harvestable organ (full symbols) and proteins (open symbols) of intercrops and pure stand at the four levels of input used in the simulations, when rain was evenly distributed over the growing period. Single points at the right site are the situations in which water supply is non-limiting.

6.3 Conclusions

Several options, which had the possibility to increase the total productivity of the intercropping systems, were studied and turned out to have different effects.
A shorter sorghum gave no increase in overall productivity. Increasing the light use efficiency of cowpea led to a better competitive position of cowpea and increased the productivity. Later planting of sorghum increased the total productivity and cowpea productivity only if sufficient rain fell. Increasing the density increased mainly the sorghum yield while decreasing the cowpea yield. With a more evenly distributed water supply, productivity only increased at the higher water supply levels.
All LER values and the ratios of productivities were still higher than one, but the trend was not always increasing as the water supply decreased (as was the case in the reference simulations).

7. Behaviour of sorghum and cowpea densities at different levels of water input

Previous chapters showed that the value of the LER depended on the intercrop density and it will also depend on the pure stand to which it is compared. Therefore, a method which can act independent of the density is more suitable. The set of equations proposed by Spitters (1983) is a good alternative. Spitters described the yield of a pure stand by equation 7.1.

$$Y_1 = \frac{N_1}{b_{1,0} + b_{1,1} * N_1} \qquad \text{equation 7.1}$$

(Y_1 is the yield of species 1, N_1 is the density, $b_{1,0}$ the reciprocal of the yield of a single plant and $b_{1,1}$ the reciprocal of the maximum yield per m^2)

For competition between to plant species, for example in an intercrop, equation 7.1 is extended to equation 7.2.

$$Y_1 = \frac{N_1}{b_{1,0} + b_{1,1} * N_1 + b_{1,2} * N_2} \qquad \text{equation 7.2}$$

(N_2 is the density of the second crops species and $b_{1,2}$ the effect of the second crop species on the first)

With the parameters $b_{1,1}$ and $b_{1,2}$, several ratios can be calculated which tell something about the competition in the mixture. The ratio $\frac{b_{1,1}}{b_{1,2}}$ indicates the ratio of intraspecific competition ($b_{1,1}$) and interspecific competition ($b_{1,2}$).
If this ratio is greater than one, intraspecific competition is greater than interspecific competition. The value of the ratio tells what the equivalent is of adding one plant of species 1, expressed in plants of species 2.
With the ratio $\frac{b_{1,1}}{b_{1,2}}$ from sorghum and cowpea, the niche differentiation index can be calculated: $\frac{b_{1,1}}{b_{1,2}} * \frac{b_{2,2}}{b_{2,1}}$.
When there would be no difference between intraspecific and interspecific competition, the niche differentiation index would be 1.0. When it is lower, the interspecific competition is higher than the intraspecific competition and when it is higher, the interspecific competition in lower than the intraspecific competition. In the latter situation, the intercropping is favourable above pure stand.

The disadvantage of the equations of Spitters is that for a good estimation of the parameters, a lot of experiments needs to be done. With simulations, this problem is overcome, since this method quickly generates a lot of results and this is done with the model explained in this report.
A range of densities (4-80 plants/m^2) for both crops was simulated at 100 and 25% of water input. The fitting was done for two amounts of water supply to see if the advantage of intercropping was different at lower water supply. For the pure stands, the simulations resulted in the following graphs for the yield of sorghum (Figure 7.1) and cowpea (Figure 7.2).

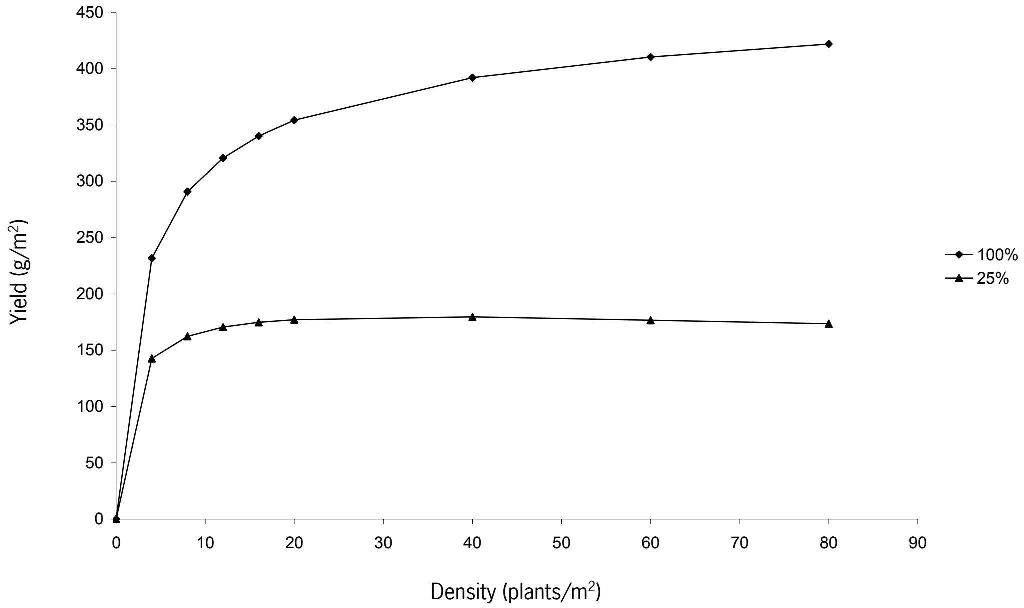

Figure 7.1. Yield of sorghum grown at different densities at 100 and 25% of normal rainfall.

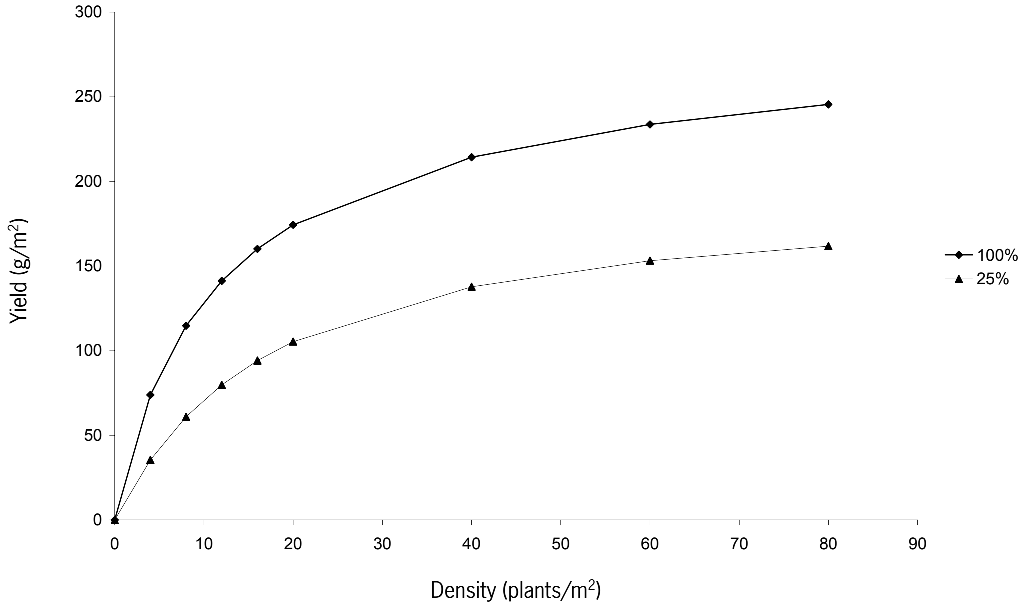

Figure 7.2. Yield of cowpea grown at different densities at 100 and 25% of normal rainfall.

Combinations of sorghum and cowpea densities were simulated at 100 and 25% of normal rain (Figures 7.3 and 7.4 show the results at 100% of normal rain and Figures 7.5 and 7.6 at 25% of normal rain). The results were fitted with equation 7.2. The obtained results for sorghum and cowpea are presented in Table 7.1.

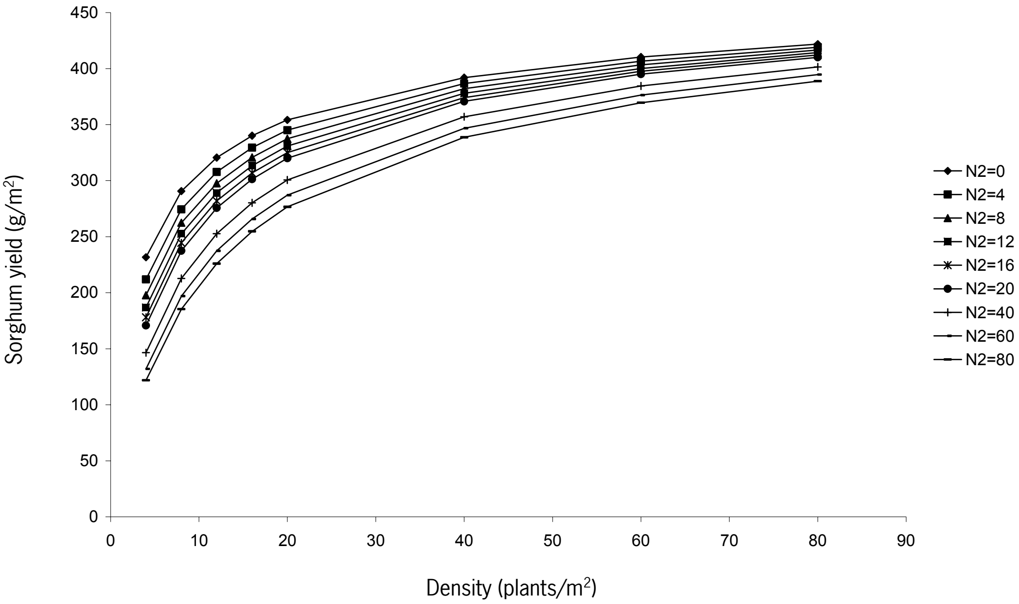

Figure 7.3. *The yield of sorghum at different densities when different densities of cowpea (N2) are added at 100% of normal rainfall.*

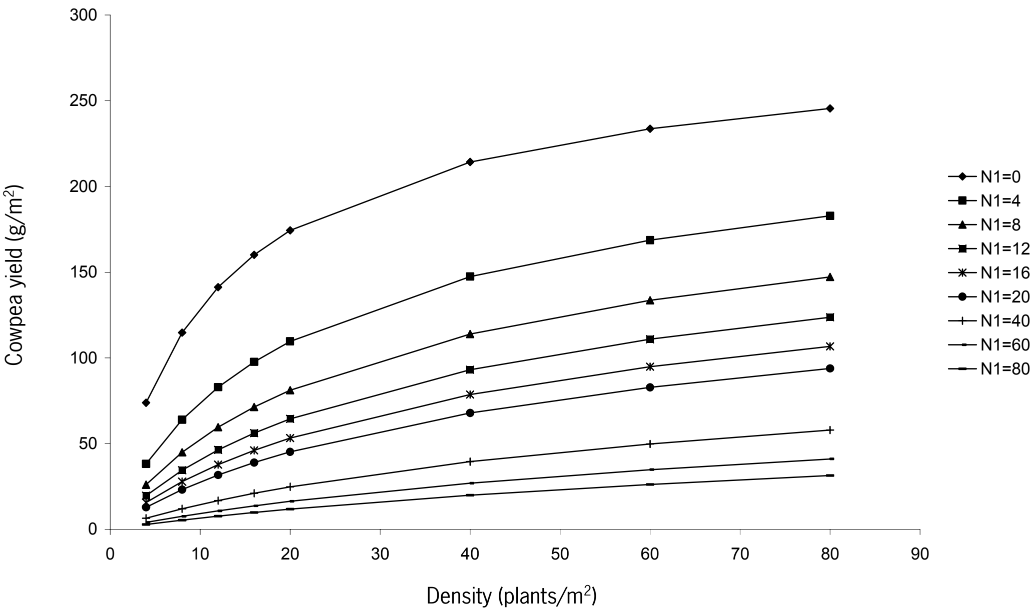

Figure 7.4. *The yield of cowpea at different densities when different densities of sorghum (N1) are added at 100% of normal rainfall.*

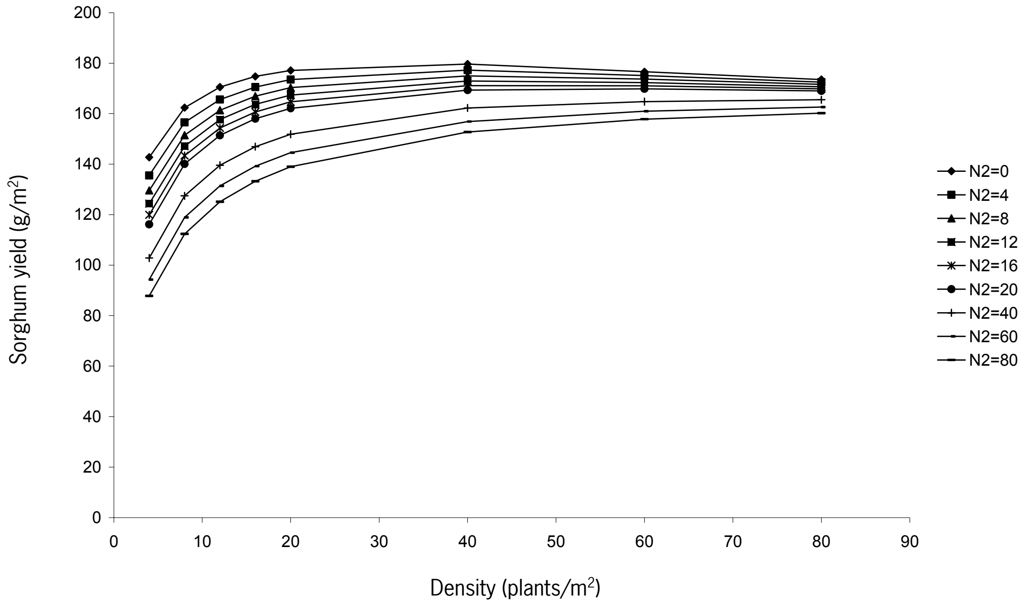

Figure 7.5. *The yield of sorghum at different densities when different densities of cowpea (N2) are added at 25% of normal rainfall.*

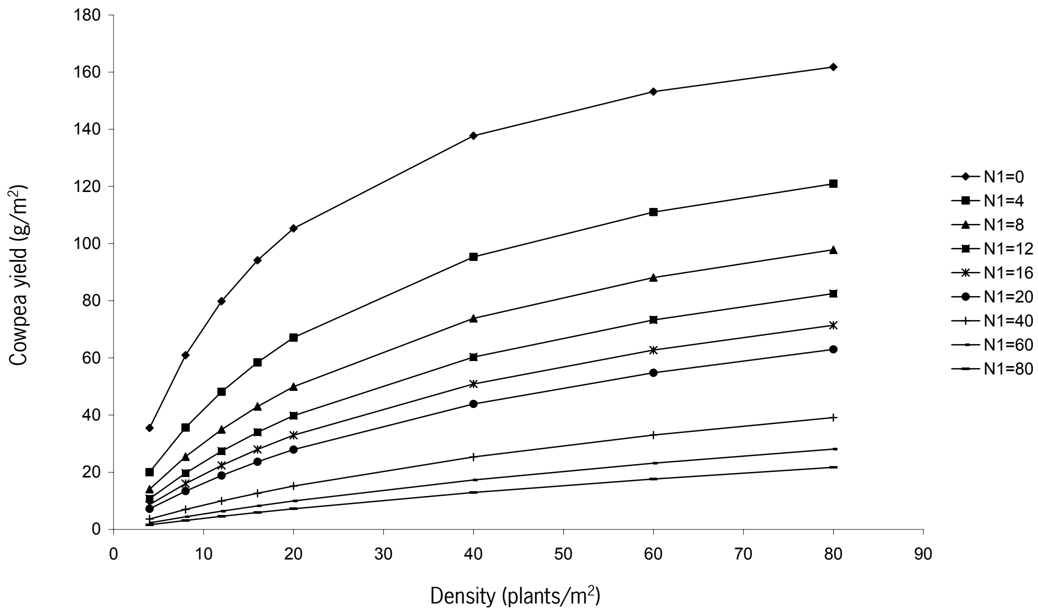

Figure 7.6. *The yield of cowpea at different densities when different densities of sorghum (N1) are added at 25% of normal rainfall.*

From Figures 7.3 and 7.4 can be seen that at adequate water supply, sorghum had higher impact on cowpea production than cowpea on sorghum production. This has changed to a situation where even more growth reduction was imposed on cowpea through sorghum when the water was reduced to 25%. The goodness of fit was at least 98.8%.

Table 7.1. The parameter values for $b_{1,0}$, $b_{1,1}$ and $b_{1,2}$ from the equation of Spitters as obtained with the results of the sorghum and cowpea simulations at 100% and 25% of normal rainfall.

		100%	$b_{1,1}/b_{1,2}$	25%	$b_{1,1}/b_{1,2}$
sorghum	$b_{s,0}$	0.01032		0.00489	
	$b_{s,s}$	0.00230		0.00566	
	$b_{s,c}$	0.00021	11.20	0.00030	18.81
cowpea	$b_{c,0}$	0.03554		0.07963	
	$b_{c,c}$	0.00387		0.00541	
	$b_{c,s}$	0.02040	0.19	0.03224	0.17

* *$b_{s,0}$, $b_{s,s}$ and $b_{s,c}$ are the parameters $b_{1,0}$, $b_{1,1}$ and $b_{1,2}$ for sorghum, respectively and $b_{c,0}$, $b_{c,c}$ and $b_{c,s}$ are the same parameters for cowpea*

As explained above, the ratio $\frac{b_{1,1}}{b_{1,2}}$ tells something about intra and interspecific competition. At 100% of rainfall, this ratio is 11.2 for sorghum and 0.19 for cowpea. So, 11.2 cowpea plants need to be added to sorghum to result in the same competition as one sorghum plant and for cowpea, just 0.19 sorghum plants are needed to obtain the same competition as one cowpea plant. In sorghum, the intraspecific competition is greater than the interspecific competition with cowpea, while in cowpea, the interspecific competition is higher than the intraspecific competition. This is also clear from Figures 7.3 and 7.4.

At 25% of rainfall, this ratio is changed to 18.8 for sorghum and 0.17 for cowpea. This means that at lower rainfall, cowpea becomes a weaker competitor for sorghum. In sorghum, more cowpea plants are needed to (18.8 instead of 11.2) get the same competition as one sorghum plant and in cowpea, slightly less plants of sorghum (0.17 instead of 0.19) are needed to get the same competition as one cowpea plant. This can depend on the higher critical water content of cowpea and their lower rooting depth, which made less water available to the crop and this became especially clear at low water supply.

The niche differentiation index is 2.12 at 100% of normal rain and at 25% of normal rain it has changed into 3.16. This means that the combination of crops is favourable at both amounts of water supply. This corresponds with the LER, which is also higher than one for all intercropping densities and water supply levels tested. The increase of the niche differentiation index with decreasing water supply corresponds to the increase in LER with decreasing water supply.

8. Discussion and overall conclusions

8.1 Model and its parameterisation

The idea about the model was to keep it as simple as possible. While keeping the simplicity of the model low, concessions were done to the accuracy of the used simulation methods. The more precise the processes are simulated the more complex the model will become. On the other hand, a more precise simulation method will often require more model parameters and every model parameter will incorporate some error, resulting in a potentially large accumulated error in the model output. Simple models are therefore likely to adequately serve the purpose of our analysis.

In the aboveground competition, the leaves are assumed to be evenly distributed over the height. In reality, the majority of the leaves will be concentrated halfway the plant height, and both the leaf area and the leaf nitrogen content are gradually decreasing towards the top and the ground (Kropff and Van Laar, 1993; Bindraban, 1999). This implies a small overestimation of the cowpea growth and a small underestimation of the sorghum growth, since the height of the cowpea is less than half the height of the sorghum.

In the model, there is not accounted for spatial arrangement (mixed intercropping, intra-cropping or row intercropping; see chapter 2), only for crop density. In reality, spatial arrangement as well as the density will influence the yields of the crops (Gilbert, 1996; Oljaca *et al.*, 2000). With the same density, but different arrangements of the crops, the yields of the component crops will be different in experiments, while the model will give the same output for all spatial arrangements.

The light use efficiency is kept constant over the growing season, but a decrease in LUE might be expected when the generative stage starts. The harvestable organs (especially the pods of cowpea) have a high protein content and proteins demand more energy for construction than carbohydrates. The yields of cowpea might therefore be lower than the simulated results.

Competition for water by two or more plant species is not easy to model. Normally, the distribution of water over competing species is based on root length or root length density (Kropff and Van Laar, 1993; Van Noordwijk and Lusiana, 1999): the plant species with the higher root length (density) obtains a higher proportion of the available water. In this way, more water can be assigned to a plant species than it needs, while the other plant gets less water than needed, although the water might be present. In the current method, this problem is overcome; both plant species have there normal transpiration and only when more water would be used than is available, the transpiration of both plant species is reduced. It is assumed that the uptake capacity of the roots is unlimited, which might not be the case. Roots will have a certain capacity for uptake of water, depending among others on species and root length density (Gregory, 1994). Also the water must be transported through the soil to the roots, which depends on soil water content and depth in the soil (Wijnja and Van Beusichem, 1998). At very low plant densities, the growth of the crops might be lower than simulated, due to restrictions in water uptake.

If the transpiration was less than potential, this was only assumed to have an effect on the daily growth rate. Other variables or parameters which might also be affected (e.g. increase of height or rooting depth) were kept constant. Water stress is also assumed to have only an effect on the day it occurs, and not affect the performance of the plant in later days. Differences of parameters values, sometimes as reaction on water stress, exist between intercrops and pure stands. For example, Fadlalla (1999) did pot experiments with sorghum and cowpea and observed that the SLA of sorghum and cowpea was not affected by water supply but did differ between pure stands and intercropping. The maximum leaf photosynthetic rate (influencing the LUE) of sorghum was affected by water supply and also differed between intercropping and pure stands. The maximum leaf photosynthetic rate of cowpea hardly differed between the cropping systems and water supply levels. These variations weren't incorporated in the model.

Parameter values for this study were obtained from literature. This means that the parameters for the same plant species come from different sources. Their values could therefore depend on a variety used in the particular experiment and on the experimental circumstances. Unmatching combinations of parameters can therefore exist. This is not a major problem since sensitivity analysis can reveal the relative importance of the different parameters. For comparing the results with literature values, the problem is bigger. Validation with results from experiments was difficult, because each experiments differs in soil type, density, location, weather and management practices from

the model. However, the results of the trends in LER and ratio of productivities of intercrops and pure stands with increasing water supply can be compared for experimental results and the results of the model simulations.
When the results of the simulations were observed, the LER, ΔWU, ΔWUE and the ratio of productivities of intercrops and pure stands revealed that the densities could have been higher than the densities applied, while the densities were already high compared to literature values.
Another note which should be kept in mind regarding the simulation results is that these simulations were done with one data set for weather. Of course, each year, weather is different and so crop performance will also be different, for example lower or higher growth through differences in radiation. For assessing trends in the behaviour of the system, this is not a problem.

8.2 Use and efficiency of the water input

In chapter 4 and 5, much information about the water use and water use efficiency is given.
Water use was highest at the highest level of water supply. However, water use efficiency was highest at the lowest amount of water supply. At this water supply level a high proportion was used for transpiration, while the there was no loss of water through the absence of percolation. This trend was seen in the pure stands as well as in the intercrops. However, aiming for the situation in which the highest water use efficiency occurs is not advisable, since production is usually low in those situations.
Generally, water use is regarded as the water lost from the soil by transpiration and evaporation and the water use efficiency is calculated from this. However, also the water which percolated was lost from the system. If this water would be incorporated in the water use and water use efficiency, the WUE will be lower and the WU will be higher at 100 and 75% of full rain, making the water use efficiency at lower levels even more profitable.
The water use efficiency in the intercrops was calculated from the total biomass or harvestable organ. Actually, it is not correct to add grams of biomass of sorghum to grams of biomass of cowpea. Sorghum will make a higher amount of biomass at the same transpiration due to a higher LUE. The ratio of sorghum and cowpea in the intercropping will also affect the WUE, as do the densities. The problem can be overcome by expressing the WUE per gram protein or per kilo joule.

8.3 What happens to the productivity at different levels of input

The model simulations made clear that with increasing inputs, the productivity increased. However, at a certain point, the water supply won't be limiting production any more and adding more water to the system won't increase the productivity. The productivity could then only be increased by alternating other aspects of the cropping system, e.g. increasing the density.
The LER was higher than one, which indicated an advantage of the intercrop over the pure stand. With decreasing water supply, the LER increased, though the increase was small. The advantage of the intercrop over the pure stands was still there. When the productivity of the intercrop was increased through higher densities or a higher LUE, the LER was lower. For later planting of sorghum and with an evenly distributed water supply, the soil water content was not sufficient to support the increase of the advantage over the pure stand.
The ratio of productivities of intercrops and pure stands also shows that the absolute productivity is higher in intercrops than in pure stands, also at high levels of water input. Even at the higher productivities (chapter 6), this is the case. The trend as explained in chapter 2 was present, but the ratio never was one or lower.
Further analysis with the equation from Spitters showed that there is always an advantage in the use of the tested intercropping system, since the so defined niche differentiation index was higher than one. The index increased when the water supply decreased, which supports the statement that at lower water supply, the intercrop is more productive than a pure stand.

However, several experiments in literature show that the LER of this intercropping system is not always higher than one and that it is not always the case that higher inputs give higher yields and lower LER. This can have different causes. Complementarity which is present in the simulation results can be absent in the experiments. For example, the LAI of the sorghum and cowpea in the experiments of Gilbert (1996) showed nearly the same growth, so there was no advantage of the faster development of cowpea leaf area. Also densities can be non-optimal (very low) which can cause unfavourable circumstances for transpiration. Rees (1986a) concluded that the LER decreased with increasing density and only at low density, the LER was higher than one. The distribution of water and limiting supply of other resources (nutrients) affect the production (Faris *et al.*, 1983). Sub-optimal growth conditions cause distractions from the hypothesis, because limitations of several growth factors are interfering with each other (for example water and nutrient deficiencies). Results of Morris *et al.* (1990) showed the same trend in the LER with different amounts of rain, but the results also showed that the absolute production depends not only on the total amount of water, but also on the distribution. Lightfoot and Tayler (1987) obtained LER's which were mainly higher than one, but distribution of rain interfered with the amount of rain, so a trend in the production or the LER against amount of water supply was not visible. In the model, the light which is not used by one crop is used by the other crop and water which is not used by one crop can be used by the other crop. So gaps in the resource use are automatically compensated, which might not be in reality.

8.4 The final goal: increasing the productivity

Productivity in the intercrops can be increased by increasing a specific resource. However, after a certain point, this doesn't help any more and other actions need to be taken to increase the productivity further. Several options which were explored in this project are an option to increase productivity, for example a higher density and varieties with a more efficient radiation use.

Also important in increasing the productivity is the question what has to be increased: Is the increase in total yield the main goal or is increasing the quality of the yield (e.g. protein content, fat content) the main point.

For many farmers, not only the harvestable organ of the crops is important, but also dry matter, which is used as construction material, fodder and fuel (Gilbert, 1996). This point was not considered here.

The final question: what is the best cropping system (intercrop or pure stand) for increasing the productivity? From the simulations can be concluded that the combination sorghum-cowpea is more productive than the pure stands of both crops, but literature cited above does not always support this. There can be concluded that the potential for high productivity is there, but several requirements need to be met, e.g. no nutrient shortage or pests should take place. It will also depend on the intercropping systems, so combinations of crops might only be favourable under very specific conditions. Elaborate experiments should be done to see if the production advantage of intercrops at high input levels would also be met over several years.

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Appendix I.
Model code

```
DEFINE_CALL PERL1(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
OUTPUT)
DEFINE_CALL PERL2(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,OUTPUT)
DEFINE_CALL LAYER(INPUT,INPUT,INPUT,OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL DIST(INPUT,INPUT,INPUT,INPUT,OUTPUT,OUTPUT,OUTPUT)
DEFINE_CALL EXTRA1(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
INPUT,INPUT,INPUT,OUTPUT,OUTPUT)
DEFINE_CALL EXTRA2(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
INPUT,INPUT,OUTPUT,OUTPUT)
DEFINE_CALL EXTRA3(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,OUTPUT)
DEFINE_CALL PENMAN(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,...
INPUT,OUTPUT,OUTPUT,OUTPUT,OUTPUT)

TITLE Simulation of mono- and intercropping
*crop 1 is sorghum, crop 2 is cowpea

INITIAL

*__________
* Crop part

* initial temperature sum of both species (0 day degrees)
INCON ITSUM=0.; IINT=0.
* base temperature for crop 1 and 2 (degrees C) (Van Heemst, 1988)
PARAM TBASE1=11.; TOPT1=30.0; TMAX1=42.0
PARAM TBASE2=8.
INCON IDEV=0.
* initial leaf area index, initial biomass, initial leaf weight,
* initial root weight and initial harvest weight for crop 1 and 2
* taken from Van Heemst (1988)
INCON ILAI1=0.0065; IBIOM1=0.88; ILEAF1=0.45; IROOT1=0.18; IHEAD1=0.00
INCON ILAI2=0.015; IBIOM2=1.44; ILEAF2=0.88;IROOT2=0.56; IPOD2=0.00
* extinction coefficient for crop 1 and 2
* sorghum from Van Heemst, cowpea from Idinoba et al.
PARAM K1=0.6
PARAM K2=0.85
* light use efficiency (g dm MJ-1 PAR)for crop 1 and 2
* value for full irrigated crop for sorghum, taken from Hammer et al.
* and Huda
* value for cowpea taken from Muchow et al. (1993), converted to PAR, measured
* from emergence to maturity
PARAM LUE1=2.5
PARAM LUE2=1.8
* function for the development of crop (fraction vs. development)
* FLEAF is fraction weight going to the leaves
* FROOT is fraction weight going to the roots
* FHARV is fraction weight going to the harvestable organs
```

```
* based on Van Heemst (partitioning)
FUNCTION FLEAF1=0.0, 0.5, 0.56,0.5, 0.6,0.475, 0.85,0.287,...
1.35,0., 2.1,0.
FUNCTION FLEAF2=0.0,0.61, 0.6,0.75, 0.95,0.537, 1.2,0.333,...
1.5,0.0, 2.1,0.0
FUNCTION FROOT1=0.0,0.167, 0.6,0.167, 0.85,0.174, 1.35,0.032,...
1.45,0.0, 2.1,0.0
FUNCTION FROOT2=0.0,0.39, 0.6,0.245, 0.95,0.119, 1.2,0.0,...
2.1,0.0
FUNCTION FHEAD1=0.0,0.0, 0.6,0.0, 0.85,0.177, 1.35,0.648,...
1.45,0.69, 1.82,1.0, 2.1,1.0
FUNCTION FPOD2=0.0,0.0, 0.95,0.0, 1.2,0.327, 1.5,0.72,...
1.7,1.0, 2.1,1.0
* the temperature sums for vegetative and generative development
PARAM TSUM11=1000.; TSUM12=600.
PARAM TSUM21=660.; TSUM22=630.
* density of crop 1 and 2 (plants m-2)
* taken from Van Heemst
PARAM DENS1=8.
PARAM DENS2=16.
*the specific leaf area (m2 g-1) (Penning de Vries et al.)
PARAM SLAST1=0.024
PARAM SLAST2=0.022
FUNCTION SLAS1=0.,0.6, 0.4,0.8, 0.6,1.3, 1.,1.1, 2.1,1.
FUNCTION SLAS2=0.,0.8, 1.,0.8, 1.2,1., 1.5,1.1, 1.8,1.25, 2.1,1.25
* parameters for the senescence of leaves
PARAM RDLEA1=0.06; RDLEA2=0.03
* parameter for defining the maximum root looting depth
* from Penning de Vries et al.
PARAM RDMAX1=0.6; RDMAX2=0.4
* parameter for defining the maximum plant height and function of plant
* height vs. tempsom (values from Penning de Vries et al.)
PARAM HMAX1=2.0; HMAX2=0.75
FUNCTION FHEI1=0.0,0.0, 0.5,1.5, 1.0,2.0, 2.1,2.
FUNCTION FHEI2=0.0,0.0, 1.0,0.75, 2.1,0.75
*------------
* Soil part

* initial water content of both layers, wilting point, field capacity
* wilting point and field capacity for loam soil (Penning de Vries et al.)
INCON IWA1=2.25; IWA2=1.755; IWA3=40.995; IWA4=45.
PARAM WP=0.11
PARAM FC=0.36
PARAM AD=0.01
PARAM EVAD=0.3
INCON IRAIN=0.
* parameter for the critical value of moisture uptake for crop 1 and 2
* P1=0.7; P2=0.5
* critical water content below which it is not all the available water
* can be taken by the plants depends on P according to
* CR1=WP+(1.-P1)*(FC-WP)=0.185
* CR2=WP+(1.-P2)*(FC-WP)=0.235
* function for the moisture uptake difficulty
```

```
FUNCTION CRIT1=0.0,0.0, 0.11,0.0, 0.185,1.0, 0.36,1.0, 1.0,1.0
FUNCTION CRIT2=0.0,0.0, 0.11,0.0, 0.235,1.0, 0.36,1.0, 1.0,1.0
FUNCTION EVAP=0.0,0.0, 0.2,0.05, 0.21,0.3, 0.35,0.9, 1.0,1.0
*__________
* General part

* Weather input: temperature and radiation per day (degrees C and MJ m-2)
* rain and irrigation
WEATHER WTRDIR='M:\W-VINES\SETUP\project intercropping in Africa\...
MODEL\'; CNTR='MLI'; ISTN=57; IYEAR=1950
* printed variables
PRINT WA11,RWA11,RAIN,PERC1,TRANL1,EVAL1,EXTR1,...
WA21,RWA21,EVAL2,TRANL2,PERC2,EXTR2,...
WA31,RWA31,EVAL3,TRANL3,PERC3,EXTR3,...
WA41,RWA41,EXTR4,PERC4,...
WATER1,WATER2,WATER3,WATE1T,WATE2T,WATE3T,...
RD1,RD2,TA,EVAPOT,TRAPOT,TRPOT1,TRPOT2,...
LAYER1,LAYER2,LAYER3,LAYER4,LAYTOT,...
HARV1,HARV2,DEV1,DEV2,HEIGH1,HEIGH2,...
LAI1,LAI2,TOTAL,...
AVAIW1,AVAIW2,AVAIW3,...
TRANS1,TRANS2,EVA,BIOM1,BIOM2,...
TORAD,IINTTO,TORAIN,PERC4T,WAT
* timer statement and integration method
FINISH DEV1>2.099
TIMER STTIME=185.; FINTIM=350.; DELT=1.; PRDEL=1.
TRANSLATION_GENERAL DRIVER='EUDRIV'


DYNAMIC
*______
* PLANT GROWTH AND DEVELOPMENT

TA=0.5*(TMMN+TMMX)
I0=0.5*RDD/1.E+6

* calculating the temperature sum for sorghum
TSUM1=INTGRL(ITSUM, RTSUM1)
RTSUM1=INSW(TA-TOPT1,TA-TBASE1,(TOPT1-TBASE1)*(1.-(TA-TOPT1)/...
(TMAX1-TOPT1)))
* calculating the temperature sum for cowpea
TSUM2=INTGRL(ITSUM, RTSUM2)
RTSUM2=(MAX(0., TA-TBASE2))/DELT

*calculating the development stage for sorghum
DEV1=MIN(DEV11,2.1)
DEV11=INTGRL(IDEV,RDEV1)
RDEV1=RTSUM1*INSW(TSUM1-TSUM11,1./TSUM11,1./TSUM12)
*calculating the development stage for cowpea
DEV2=MIN(DEV21,2.1)
DEV21=INTGRL(IDEV,RDEV2)
RDEV2=RTSUM2*INSW(TSUM2-TSUM21,1./TSUM21,1./TSUM22)
```

```
* calculating the total leaf area index
TOTLAI=LAI1+LAI2

* light interception: two layer model from Tsubo and Walker
LAIS1=(HEIGH1-HEIGH2)/HEIGH1*LAI1
LAIS2=HEIGH2/HEIGH1*LAI1
IINT11=I0*(1.-EXP(-K1*LAIS1))
IINT12=I0*EXP(-K1*LAIS1)*(1.-EXP(-K1*LAIS2-K2*LAI2))*...
((K1*LAIS2)/NOTNUL((K1*LAIS2+K2*LAI2)))
IINT2=I0*EXP(-K1*LAIS1)*(1.-EXP(-K1*LAIS2-K2*LAI2))*...
((K2*LAI2)/NOTNUL((K1*LAIS2+K2*LAI2)))
IINT1=IINT11+IINT12

TORAD=INTGRL(IINT,RRAD)
RRAD=I0/DELT
IINTTO=TIINT1+TIINT2
TIINT1=INTGRL(IINT,RINT1)
RINT1=IINT1/DELT
TIINT2=INTGRL(IINT,RINT2)
RINT2=IINT2/DELT*INSW(DEV2-2.099,1.,0.)

* calculating the growth (g dm m-2)
GROPO1=IINT1*LUE1
GROPO2=IINT2*LUE2*INSW(DEV2-2.099,1.,0.)

* growth is limited by water. WATER1 and WATER2 give the fraction growth
* from the potential growth as determined by the water limitations.
* WATER1 and WATER2 are calculated in the soil part of the model
CGRO1=GROPO1*WATER1
CGRO2=GROPO2*WATER2

* calculating the total biomass for species 1 and 2 (g dm m-2)
BIOM1=INTGRL(IBIOM1,RBIOM1)
RBIOM1=CGRO1/DELT
BIOM2=INTGRL(IBIOM2,RBIOM2)
RBIOM2=CGRO2/DELT

* calculating the leaf weight for species 1 and 2 (g dm m-2)
WLEAF1=INTGRL(ILEAF1,RLEAF1)
RLEAF1=CGRO1*AFGEN(FLEAF1,DEV1)/DELT
WLEAF2=INTGRL(ILEAF2,RLEAF2)
RLEAF2=CGRO2*AFGEN(FLEAF2,DEV2)/DELT

* calculating the leaf area index
LAI1=INTGRL(ILAI1, RLAI1)
RLAI1=GRLEA1-DLEAF1
GRLEA1=RLEAF1*SLA1/DELT
DLEAF1=INSW(TSUM1-TSUM11,0.,RDLEA1*LAI1/DELT)
SLA1=SLAST1*AFGEN(SLAS1,DEV1)

LAI2=INTGRL(ILAI2, RLAI2)
RLAI2=GRLEA2-DLEAF2
GRLEA2=RLEAF2*SLA2/DELT
```

```
DLEAF2=INSW(TSUM2-TSUM21,0.,RDLEA2*LAI2/DELT)*...
INSW(DEV2-2.099,1.,0.)
SLA2=SLAST2*AFGEN(SLAS2,DEV2)

* calculating the height of the crop plant
HEIGH1=0.05+AFGEN(FHEI1,DEV1)
HEIGH2=0.05+AFGEN(FHEI2,DEV2)

* calculating the root weight
RW1=INTGRL(IROOT1, RROOT1)
RROOT1=CGRO1*AFGEN(FROOT1, DEV1)/DELT
RW2=INTGRL(IROOT2, RROOT2)
RROOT2=CGRO2*AFGEN(FROOT2, DEV2)/DELT

* calculating the rooting depth of both species.
* the rooting depth is can have a maximum of RDMAX
RD11=HEIGH1*RDMAX1/HMAX1
RD21=HEIGH2*RDMAX2/HMAX2
RD1=MIN(RD11,RDMAX1)
RD2=MIN(RD21,RDMAX2)

* calculating the weight of harvestable product (g m-2)
* data from Van Heemst (1988)
HARV1=0.8*HEAD1
HEAD1=INTGRL(IHEAD1,RHEAD1)
RHEAD1=CGRO1*AFGEN(FHEAD1,DEV1)/DELT
HARV2=0.8*POD2
POD2=INTGRL(IPOD2,RPOD2)
RPOD2=CGRO2*AFGEN(FPOD2,DEV2)/DELT

*______
* SOIL WATER PART
* the accumulated rain
TORAIN=INTGRL(IRAIN,RRAIN)
RRAIN=RAIN/DELT

*calculation of the water content of each layer
WAT=WA11+WA21+WA31+WA41
WA11=INTGRL(IWA1,RWA11)
RWA11=(RAIN+EXTR1-TRANL1-EVAL1-PERC1)/DELT
EXTR1=(EXT111+EXT112)+(EXT122+EXT121)
WA21=INTGRL(IWA2,RWA21)
RWA21=(PERC1-TRANL2-EVAL2-PERC2+EXTR2)/DELT
EXTR2=(EXT211+EXT212-EXT111)+(EXT221+EXT222-EXT121)
WA31=INTGRL(IWA3,RWA31)
RWA31=(PERC2-TRANL3-EVAL3-PERC3+EXTR3)/DELT
EXTR3=(EXTR31-EXT112-EXT211)+(EXTR32-EXT122-EXT221)
WA41=INTGRL(IWA4,RWA41)
RWA41=(PERC3-PERC4+EXTR4)/DELT
EXTR4=(-EXT212-EXTR31)+(-EXT222-EXTR32)

* call of the EXTRA-subroutines to calculate the water which comes available through root growth
CALL EXTRA1(RD1,RD2,EVAD,LAYER2,LAYER3,WA21,WA31,TRANL2,EVAL2,TRANL3,...
```

```
EVAL3,EXT111,EXT112)
CALL EXTRA1(RD2,RD1,EVAD,LAYER2,LAYER3,WA21,WA31,TRANL2,EVAL2,TRANL3,...
EVAL3,EXT121,EXT122)
CALL EXTRA2(RD1,RD2,EVAD,LAYER3,LAYER4,WA31,WA41,TRANL3,EVAL3,RDMAX1,...
EXT211,EXT212)
CALL EXTRA2(RD2,RD1,EVAD,LAYER3,LAYER4,WA31,WA41,TRANL3,EVAL3,RDMAX2,...
EXT221,EXT222)
CALL EXTRA3(RD1,RD2,EVAD,WA41,LAYER4,RDMAX1,EXTR31)
CALL EXTRA3(RD2,RD1,EVAD,WA41,LAYER4,RDMAX2,EXTR32)

* calculating the thickness of the two layers. Layer 1 is the
* rooting depth of the swallower crop (function MIN choose
* the smallest of the two rooting depths), layer 2 goes from the bottom
* of layer 1 to the rooting depth of the second crop and is determined
* by the absolute difference of the two rooting depths
DEEP=MAX(RD1,RD2)
SWAL=MIN(RD1,RD2)
RLAY1=LAYER1/LAYTOT
RLAY2=LAYER2/LAYTOT
RLAY3=LAYER3/LAYTOT
LAYTOT=LAYER1+LAYER2+LAYER3
LAYER4=0.6-LAYTOT
CALL LAYER(DEEP,SWAL,EVAD,LAYER1,LAYER2,LAYER3)
CALL DIST(LAYER1,LAYER2,LAYER3,RD1,FRRD11,FRRD12,FRRD13)
CALL DIST(LAYER1,LAYER2,LAYER3,RD2,FRRD21,FRRD22,FRRD23)
CALL DIST(LAYER1,LAYER2,LAYER3,EVAD,FREVA1,FREVA2,FREVA3)

* the percolation depends on the water content after rain, irrigation,
* transpiration and evaporation and is calculated in the subroutines
* PERCL1 and PERCL2. If this water content is more than field capacity
* the difference between water content and field capacity percolates
CALL PERL1(LAYER1,WA11,FC,RAIN,IRRIIN*PUSH,TRANL1,EVAL1,EXTR1,...
PERC1)
CALL PERL2(LAYER2,WA21,FC,PERC1,TRANL2,EVAL2,EXTR2,PERC2)
CALL PERL2(LAYER3,WA31,FC,PERC2,TRANL3,EVAL3,EXTR3,PERC3)
CALL PERL2(LAYER4,WA41,FC,PERC3,0.,0.,EXTR4,PERC4)

* accumulated percolation from the fourth layer
PERC4T=INTGRL(ITIC,RPERC)
RPERC=PERC4/DELT

* calculating the available water in layer 1 and layer 2, as the
* difference between the actual water content and the wilting point
* if the water content is lower than the wilting point, there is no
* water available
AVAIW1=INSW(AVA1,0.,AVA1)
AVA1=(WA11+RAIN+IRRIIN*PUSH)-WP*LAYER1*1000.
AVAIW2=INSW(AVA2,0.,AVA2)
AVA2=WA21-WP*LAYER2*1000.
AVAIW3=INSW(AVA3,0.,AVA3)
AVA3=WA31-WP*LAYER3*1000.
AVAIW4=INSW(AVA4,0.,AVA4)
AVA4=WA41-WP*LAYER4*1000.
```

```
AVAV1=INSW(AVAEV1,0.,AVAEV1)
AVAV2=INSW(AVAEV2,0.,AVAEV2)
AVAV3=INSW(AVAEV3,0.,AVAEV3)
AVAEV1=INSW(AVAIW1-0.0001,WA11+RAIN+IRRIIN*PUSH-AD*LAYER1*1000.,...
(WP-AD)*LAYER1*1000.)
AVAEV2=INSW(AVAIW2-0.0001,WA21-AD*LAYER2*1000.,(WP-AD)*LAYER2*1000.)
AVAEV3=INSW(AVAIW3-0.0001,WA31-AD*LAYER3*1000.,(WP-AD)*LAYER3*1000.)
AVW1T=AVAIW1+AVAV1
AVW2T=AVAIW2+AVAV2
AVW3T=AVAIW3+AVAV3

* calculating the potential transpiration (total and per plant species) and evaporation (mm d-1)
CALL PENMAN(TA,VP,RDD,TOTLAI,LAI1,DEV2,WN,IINT1,IINT2,EVAPOT,TRAPOT,...
TRPOT1,TRPOT2)

* calculation of potential available water per plant species per layer
* species 1
ASP1L1=AFGEN(CRIT1,WA11/(LAYER1*1000.))*WA11*INSW(FRRD11-0.0001,0.,1.)
ASP1L2=AFGEN(CRIT1,WA21/(LAYER2*1000.))*WA21*INSW(FRRD12-0.0001,0.,1.)
ASP1L3=AFGEN(CRIT1,WA31/(LAYER3*1000.))*WA31*INSW(FRRD13-0.0001,0.,1.)
* species 2
ASP2L1=AFGEN(CRIT2,WA11/(LAYER1*1000.))*WA11*...
INSW(FRRD21-0.0001,0.,1.)*INSW(DEV2-2.099,1.,0.)
ASP2L2=AFGEN(CRIT2,WA21/(LAYER2*1000.))*WA21*...
INSW(FRRD22-0.0001,0.,1.)*INSW(DEV2-2.099,1.,0.)
ASP2L3=AFGEN(CRIT2,WA31/(LAYER3*1000.))*WA31*...
INSW(FRRD23-0.0001,0.,1.)*INSW(DEV2-2.099,1.,0.)
* evaporation
AEVAL1=AFGEN(EVAP,WA11/(LAYER1*1000.))*INSW(FREVA1-0.0001,0.,1.)*WA11
AEVAL2=AFGEN(EVAP,WA11/(LAYER1*1000.))*INSW(FREVA2-0.0001,0.,1.)*WA21
AEVAL3=AFGEN(EVAP,WA11/(LAYER1*1000.))*INSW(FREVA3-0.0001,0.,1.)*WA31

* fraction absorption per layer for each plant species or for evaporation,
* based on the potential water uptake
FSP1L1=ASP1L1/NOTNUL(ASP1L1+ASP1L2+ASP1L3)
FSP1L2=ASP1L2/NOTNUL(ASP1L1+ASP1L2+ASP1L3)
FSP1L3=ASP1L3/NOTNUL(ASP1L1+ASP1L2+ASP1L3)
FSP2L1=ASP2L1/NOTNUL(ASP2L1+ASP2L2+ASP2L3)
FSP2L2=ASP2L2/NOTNUL(ASP2L1+ASP2L2+ASP2L3)
FSP2L3=ASP2L3/NOTNUL(ASP2L1+ASP2L2+ASP2L3)
FEVL1=AEVAL1/NOTNUL(AEVAL1+AEVAL2+AEVAL3)
FEVL2=AEVAL2/NOTNUL(AEVAL1+AEVAL2+AEVAL3)
FEVL3=AEVAL3/NOTNUL(AEVAL1+AEVAL2+AEVAL3)

* LAYER 1: calculating actual uptake
* calculation of transpiration in the first layer
S1POT1=TRPOT1*FSP1L1* AFGEN(CRIT1,WA11/(LAYER1*1000.))
S2POT1=TRPOT2*FSP2L1* AFGEN(CRIT2,WA11/(LAYER1*1000.))*INSW(DEV2-2.099,1.,0.)
EVAPL1=EVAPOT*FEVL1* AFGEN(EVAP,WA11/(LAYER1*1000.))
* total demanded from available water
TOTL1P=S1POT1+S2POT1+EVAPL1
* reduction if demanded is more than available
FR1=MIN(1.,AVW1T/NOTNUL(TOTL1P))
```

```
* actual uptake per species in layer 1
TRAN11=S1POT1*FR1
TRAN21=S2POT1*FR1
EVAL1=EVAPL1*FR1

* LAYER2: uptake
S1POT2=TRPOT1*FSP1L2* AFGEN(CRIT1,WA21/(LAYER2*1000.))
S2POT2=TRPOT2*FSP2L2* AFGEN(CRIT2,WA21/(LAYER2*1000.))*INSW(DEV2-2.099,1.,0.)
EVAPL2=EVAPOT*FEVL2* AFGEN(EVAP,WA11/(LAYER1*1000.))
TOTL2P=S1POT2+S2POT2+EVAPL2
FR2=MIN(1.,AVW2T/NOTNUL(TOTL2P))
TRAN12=S1POT2*FR2
TRAN22=S2POT2*FR2
EVAL2=EVAPL2*FR2

* LAYER3: uptake
S1POT3=TRPOT1*FSP1L3* AFGEN(CRIT1,WA31/(LAYER3*1000.))
S2POT3=TRPOT2*FSP2L3* AFGEN(CRIT2,WA31/(LAYER3*1000.))*INSW(DEV2-2.099,1.,0.)
EVAPL3=EVAPOT*FEVL3* AFGEN(EVAP,WA11/(LAYER1*1000.))
TOTL3P=S1POT3+S2POT3+EVAPL3
FR3=MIN(1.,AVW3T/NOTNUL(TOTL3P))
TRAN13=S1POT3*FR3
TRAN23=S2POT3*FR3
EVAL3=EVAPL3*FR3

* total transpiration for species 1 and 2 and total evaporation
TRANS1=TRAN11+TRAN12+TRAN13
TRANS2=TRAN21+TRAN22+TRAN23
EVA=EVAL1+EVAL2+EVAL3

* calculation of total potential and actual transpiration
* total potential transpiration species 1 and 2
TRSP1P=INTGRL(ITIC,RTR1P)
RTR1P=TRPOT1/DELT
TRSP2P=INTGRL(ITIC,RTR2P)
RTR2P=TRPOT2/DELT
* total actual transpiration species 1 and 2
TRSP1T=INTGRL(ITIC,RTR1)
RTR1=TRANS1/DELT
TRSP2T=INTGRL(ITIC,RTR2)
RTR2=TRANS2/DELT
* calculation of total actual and potential evaporation
EVAT=INTGRL(ITIC,REVA)
REVA=EVA/DELT
EVAPT=INTGRL(ITIC,REVAP)
REVAP=EVAPOT/DELT

* factor for the reduction of growth, given by the ratio actual/potential
* transpiration
WATER1=TRANS1/NOTNUL(TRPOT1)
WATER2=TRANS2/NOTNUL(TRPOT2)
WATER3=EVA/NOTNUL(EVAPOT)*FCNSW(EVA,0.,0.,1.)
* overall growth reduction
```

```
WATE1T=TRSP1T/NOTNUL(TRSP1P)
WATE2T=TRSP2T/NOTNUL(TRSP2P)
WATE3T=EVAT/NOTNUL(EVAPT)

* transpiration per layer
TRANL1=TRAN11+TRAN21
TRANL2=TRAN12+TRAN22
TRANL3=TRAN13+TRAN23

END
* sorghum pure stand
INCON ILAI2=0.; IBIOM2=0.; ILEAF2=0.;IROOT2=0.; IPOD2=0.
END
* cowpea pure stand
INCON ILAI2=0.015; IBIOM2=1.44; ILEAF2=0.88;IROOT2=0.56; IPOD2=0.00
INCON ILAI1=0.; IBIOM1=0.; ILEAF1=0.;IROOT1=0.; IHEAD1=0.
END
STOP
```

```
      SUBROUTINE PERL1(LAYER,WC,FC,RAIN,IRRI,TRAN,EVA,EXTR,PERC)
      IMPLICIT REAL (A-Z)
      SAVE

      FCW=FC*LAYER*1000.
      IF (WC+RAIN+IRRI+EXTR-TRAN-EVA.LT.FCW)
     $ PERC1=0.
      IF (WC+RAIN+IRRI+EXTR-TRAN-EVA.GE.FCW)
     $ PERC1=WC-FCW+RAIN+IRRI+EXTR-TRAN-EVA
      RETURN
      END

      SUBROUTINE PERL2(LAYER,WC,FC,PERC,TRAN,EVA,EXTR,PERC)
      IMPLICIT REAL (A-Z)
      SAVE

      FCW=FC*LAYER*1000.
      IF (WC+PERC1+EXTR-TRAN-EVA.LT.FCW)
     $ PERC2=0.
      IF (WC+PERC1+EXTR-TRAN-EVA.GE.FCW)
     $ PERC2=WC-FCW+PERC1+EXTR-TRAN-EVA
      RETURN
      END

      SUBROUTINE LAYER(DEEP,SHAL,DEVA,L1,L2,L3)
      IMPLICIT REAL (A-Z)

      IF ((DEEP.LT.DEVA).AND.(SHAL.LT.DEVA)) THEN
       L1=SHAL
       L2=DEEP-SHAL
       L3=DEVA-DEEP
      ENDIF
      IF ((DEEP.GE.DEVA).AND.(SHAL.LT.DEVA)) THEN
       L1=SHAL
       L2=DEVA-SHAL
       L3=DEEP-DEVA
      ENDIF
      IF ((DEEP.GE.DEVA).AND.(SHAL.GE.DEVA)) THEN
       L1=DEVA
       L2=SHAL-DEVA
       L3=DEEP-SHAL
      ENDIF
      END

      SUBROUTINE DIST(L1,L2,L3,DEPTH,FRL1,FRL2,FRL3)
      IMPLICIT REAL (A-Z)

       FRL1=L1/(L1+L2+L3)
       FRL2=L2/(L1+L2+L3)
       FRL3=L3/(L1+L2+L3)
      IF (L1+L2.GE.DEPTH) THEN
       FRL1=L1/(L1+L2)
       FRL2=L2/(L1+L2)
       FRL3=0.
      ENDIF
      IF (L1.GE.DEPTH) THEN
       FRL1=1.
       FRL2=0.
       FRL3=0.
      ENDIF
      END
```

```
 SUBROUTINE EXTRA1(RDA,RDB,DEVA,LAYER1,LAYER2,WA1,WA2,TRANS1,
$ EVA1,TRANS2,EVA2,EXTR1,EXTR2)
 IMPLICIT REAL (A-Z)

 IF ((RDA.LT.RDB).AND.(RDA.LT.DEVA)) THEN
   IF (WA1.GE.0.) THEN
   EXTR1=0.01*(WA1-TRANS1-EVA1)/LAYER1
   EXTR2=0.
     IF (0.01.GE.LAYER1) THEN
     EXTR1=WA1-TRANS1-EVA1
       IF (WA2.GE.0.) THEN
       EXTR2=(0.01-LAYER1)*(WA2-TRANS2-EVA2)/LAYER2
       ELSE
       EXTR2=0.
       ENDIF
     ENDIF
   ELSE
   EXTR1=0.
     IF (0.01.GE.LAYER1) THEN
       IF (WA2.GE.0.) THEN
       EXTR2=(0.01-LAYER1)*(WA2-TRANS2-EVA2)/LAYER2
       ELSE
       EXTR2=0.
       ENDIF
     ENDIF
   ENDIF
 ELSE
 EXTR1=0.
 EXTR2=0.
 ENDIF
 END

 SUBROUTINE EXTRA2(RDA,RDB,DEVA,LAYER1,LAYER2,WA1,WA2,TRANS1,
$ EVA1,RDMAX,EXT1,EXT2)
 IMPLICIT REAL (A-Z)

 IF ((RDA.GE.RDB).AND.(RDA.LT.DEVA).AND.(RDA.LT.RDMAX)) THEN
   IF (WA1.GE.0.0) THEN
   EXT1=0.01*(WA1-TRANS1-EVA1)/LAYER1
   EXT2=0.0
     IF (0.01.GE.LAYER1) THEN
     EXT1=WA1-TRANS1-EVA1
       IF (WA2.GE.0.) THEN
       EXT2=(0.01-LAYER1)*WA2/LAYER2
       ELSE
       EXT2=0.
       ENDIF
     ENDIF
   ELSE
   EXT1=0.
     IF (0.01.GE.LAYER1) THEN
       IF (WA2.GE.0.) THEN
       EXT2=(0.01-LAYER1)*WA2/LAYER2
       ELSE
       EXT2=0.
       ENDIF
     ENDIF
   ENDIF
 ELSE
```

```
      IF ((RDA.LT.RDB).AND.(RDA.GE.DEVA).AND.(RDA.LT.RDMAX)) THEN
        IF (WA1.GE.0.0) THEN
        EXT1=0.01*(WA1-TRANS1-EVA1)/LAYER1
        EXT2=0.0
          IF (0.01.GE.LAYER1) THEN
          EXT1=WA1-TRANS1-EVA1
            IF (WA2.GE.0.) THEN
            EXT2=(0.01-LAYER1)*WA2/LAYER2
            ELSE
            EXT2=0.
            ENDIF
          ENDIF
        ELSE
        EXT1=0.
          IF (0.01.GE.LAYER1) THEN
            IF (WA2.GE.0.) THEN
            EXT2=(0.01-LAYER1)*WA2/LAYER2
            ELSE
            EXT2=0.
            ENDIF
          ENDIF
        ENDIF
      ELSE
      EXT1=0.
      EXT2=0.
      ENDIF
    ENDIF
    END

    SUBROUTINE EXTRA3(RDA,RDB,DEVA,WA1,LAYER1,RDMAX,EXTRA)
    IMPLICIT REAL (A-Z)

    IF ((RDA.GE.RDB).AND.(RDA.GE.DEVA).AND.(RDA.LT.RDMAX)) THEN
      IF (WA1.GE.0.) THEN
      EXTRA=0.01*WA1/LAYER1
        IF (LAYER1.LT.0.01) THEN
        EXTRA=WA1
        ENDIF
      ENDIF
    ELSE
    EXTRA=0.
    ENDIF
    END

    SUBROUTINE PENMAN(DAVTMP,VP,DTR,LAI,LAI1,DEV2,WN,IN1,IN2,PEVAP,
   $ PTRAN,PTRAN1,PTRAN2)
    IMPLICIT REAL (A-Z)

    DTRJM2 = DTR
    BOLTZM = 5.668E-8
    LHVAP  = 2.4E6
    PSYCH  = 0.067
```

```
      BBRAD  = BOLTZM * (DAVTMP+273.)**4 * 86400.
      SVP    = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
      SLOPE  = 4158.6 * SVP / (DAVTMP + 239.)**2
      RLWN   = BBRAD * MAX(0.,0.55*(1.-VP/SVP))
      NRADS  = DTRJM2 * (1.-0.15) - RLWN
      NRADC  = DTRJM2 * (1.-0.25) - RLWN
      PENMRS = NRADS * SLOPE/(SLOPE+PSYCH)
      PENMRC = NRADC * SLOPE/(SLOPE+PSYCH)

      WDF    = 2.63 * (1.0 + 0.54 * WN)
      PENMD  = LHVAP * WDF * (SVP-VP) * PSYCH/(SLOPE+PSYCH)

      IF (DEV2.LT.2.099) THEN
        PEVAP  =     EXP(-LAI)  * (PENMRS + PENMD) / LHVAP
        PTRAN  = (1.-EXP(-LAI)) * (PENMRC + PENMD) / LHVAP
        PTRAN1=PTRAN*IN1/NOTNUL(IN1+IN2)
        PTRAN2=PTRAN*IN2/NOTNUL(IN1+IN2)
      ELSE
        PEVAP= EXP(-LAI)*(PENMRS+PENMD)/LHVAP
        PTRAN1=(1.-EXP(-LAI1))*(PENMRC+PENMD)/LHVAP
        PTRAN2=0.
      ENDIF



      RETURN
      END

ENDJOB
```

Appendix II.
List of abbreviations in the model code

Main model

Name	description	unit
AD	fractional water content in air dry soil	-
AEVAL(1-3)	available water for evaporation in layer 1-3	mm
ASP1L(1-3)	available water for transpiration of sorghum in layer 1-3	mm
ASP2L(1-3)	available water for transpiration of cowpea in layer 1-3	mm
AVA(1-4)	calculated plant available water in layer 1-4	mm
AVAEV(1-3)	calculated water for evaporation below wiling point	mm
AVAIW(1-4)	plant available water in layer 1-4	mm
AVAV(1-3)	water for evaporation below wilting point in layer 1-3	mm
AVW(1-3)T	total available water for evaporation in layer 1-3	mm
BIOM(1-2)	total accumulated biomass for sorghum (1) and cowpea (2)	g/m^2
CGRO(1-2)	actual daily growth rate	$g/m^2/d$
CRIT(1-2)	function for the difficulty of water uptake for sorghum (1) and cowpea	
DEEP	rooting depth of the deepest rooting species	m
DEV(1-2)	development stage of sorghum (1) and cowpea (2)	-
DEV(1-2)1	calculated development stage of sorghum (1) and cowpea (2)	-
DLEAF(1-2)	senescence of the leaf area index of sorghum (1) and cowpea (2)	1/d
EVA	actual evaporation	mm
EVAD	soil layer from which water for evaporation is taken	m
EVAL(1-3)	water uptake for evaporation from layer 1-3	mm
EVAPL(1-3)	potential evaporation from layer 1-3	mm
EVAPOT	potential evaporation	mm
EVAPT	total potential evaporation	mm
EVAT	total actual evaporation	mm
EXT111	extra water for sorghum from the second layer	mm
EXT112	extra water for sorghum from the third layer when growing through the second layer	mm
EXT121	extra water for cowpea from the second layer	mm
EXT122	extra water for cowpea from the third layer when growing through the second layer	mm
EXT211	extra water for sorghum from the third layer	mm
EXT212	extra water for sorghum from the fourth layer when growing through the third layer	mm
EXT221	extra water for cowpea from the third layer	mm
EXT222	extra water for cowpea from the fourth layer when growing through the third layer	mm
EXTR31	extra water for sorghum from the fourth layer	mm
EXTR32	extra water for cowpea from the fourth layer	mm
EXTR(1-4)	change of amount of water through growth of roots in layer 1-4	mm
FC	fractional water content at field capacity	-
FEVL(1-3)	fraction of evaporation demand in total water demand in In layer 1-3	-
FHEAD1	function for the partitioning of newly formed dry weight to the sorghum heads	
FHEI(1-2)	function for the plant height depending on development stage	
FLEAF(1-2)	function for the partitioning of newly formed dry weight to the leaves	
FPOD2	function for the partitioning of newly formed dry weight to the cowpea pods	

FR(1-3)	correction factor for potential uptake of transpiration and evaporation water	-
FREVA(1-3)	fraction of evaporation layer in layer 1-3	-
FROOT(1-2)	function for the partitioning of newly formed dry weight to the roots	
FRRD1(1-3)	fraction of roots of sorghum in layer 1-3	-
FRRD2(1-3)	fraction of roots of cowpea in layer 1-3	-
FSP1L(1-3)	fraction of total available water for transpiration of sorghum in layer 1-3	-
FSP2L(1-3)	fraction of total available water for transpiration of cowpea in layer 1-3	-
GRLEA(1-2)	growth of the leaf area index of sorghum (1) and cowpea (2)	1/d
GROPO(1-2)	daily potential growth rate of sorghum (1) and cowpea (2)	g/m^2
HARV(1-2)	weight of the net harvestable organ of sorghum (1) and and cowpea (2)	g/m^2
HEAD1	ear weight of sorghum	g/m^2
HEIGH(1-2)	height of sorghum (1) and cowpea (2)	m
HMAX(1-2)	maximum plant height of sorghum (1) and cowpea (2)	m
IBIOM(1-2)	initial total biomass of sorghum (1) and cowpea (2)	g/m^2
IHEAD1	initial weight of the sorghum heads	g/m^2
IINT(1-2)	radiation intercepted by sorghum (1) and cowpea (2)	MJ/m^2
IINT11	radiation intercepted by sorghum in the upper leaf layer	MJ/m^2
IINT12	radiation intercepted by sorghum in the lower leaf layer	MJ/m^2
IINTTO	total intercepted radiation by both crops	MJ/m^2
ILAI(1-2)	initial leaf area index of sorghum (1) and cowpea (2)	-
ILEAF(1-2)	initial leaf weight of sorghum (1) and cowpea (2)	g/m^2
I0	incoming daily global PAR	MJ/m^2
IPOD2	initial weight of the cowpea pods	g/m^2
IROOT(1-2)	initial root weight of sorghum (1) and cowpea (2)	g/m^2
ITSUM	initial value of the temperature sum	°Cd
IWA(1-4)	initial amount of water in soil layer 1-4	mm
K(1-2)	extinction coefficient for radiation of sorghum (1) and cowpea (2)	-
LAI(1-2)	leaf area index of sorghum (1) and cowpea (2)	-
LAIS1	leaf area index of sorghum in the upper leaf layer	-
LAIS2	leaf area index of sorghum in the lower leaf layer	-
LAYER(1-4)	thickness of layer 1-4	m
LAYTOT	total thickness of layers 1-3	m
LUE(1-2)	light use efficiency of sorghum (1) and cowpea (2)	g/MJ PAR
PERC(1-4)	percolation from layer 1-4	mm
PERC4T	total percolation from the lowest layer	mm
POD2	pod weight of cowpea	g/m^2
RAIN	amount of rainfall on a certain day	mm
RBIOM(1-2)	rate of change in total accumulated biomass	$g/m^2/d$
RD(1-2)	rooting depth of sorghum (1) and cowpea (2)	m
RD1(1-2)	calculated rooting depth of sorghum (1) and cowpea (2)	m
RDD	daily radiation	$J/m^2/d$
RDEV(1-2)	rate of change of development stage of sorghum (1) and cowpea (2)	1/d
RDLEA(1-2)	dead rate of the leaves of sorghum (1) and cowpea (2)	1/d
RDMAX(1-2)	maximum rooting depth of sorghum (1) and cowpea (2)	m
REVA	rate of change of total actual evaporation	mm/d
REVAP	rate of change of total potential evaporation	mm/d
RHEAD1	rate of change of the ear weight	$g/m^2/d$
RINT(1-2)	rate of change of total intercepted radiation by sorghum (1) and	$MJ/m^2/d$

	cowpea (2)	
RLAI(1-2)	rate of change of leaf area index of sorghum (1) and cowpea (2)	1/d
RLAY(1-3)	fraction of layer 1-3 in total of layers 1-3	-
RLEAF(1-2)	rate of change of leaf weight of sorghum (1) and cowpea (2)	$g/m^2/d$
RPERC	rate of change of total percolation from the lowest layer	mm/d
RPOD2	rate of change of the pod weight of cowpea	$g/m^2/d$
RRAD	rate of change in total radiation	$MJ/m^2/d$
RRAIN	rate of change of total amount of rainfall	mm/d
RROOT(1-2)	rate of change in root weight of sorghum (1) and cowpea (2)	$g/m^2/d$
RTR(1-2)	rate of change of total actual transpiration of sorghum (1) and cowpea (2)	mm/d
RTR(1-2)P	rate of change of total potential transpiration of sorghum (1) and cowpea (2)	mm/d
RTSUM(1-2)	rate of change of temperature sum of sorghum (1) and cowpea (2)	°C/d
RW(1-2)	root weight of sorghum (1) and cowpea (2)	g/m^2
RWA(1-2)1	rate of change of amount of water of layer 1-4	mm/d
S1POT(1-3)	potential transpiration of sorghum taken from layer 1-3	mm
S2POT(1-3)	potential transpiration of cowpea taken from layer 1-3	mm
SHAL	rooting depth of the most shallow rooting species	m
SLA(1-2)	specific leaf area at certain development stage of sorghum (1) and cowpea (2)	m^2/g
SLAS(1-2)	function for the variation of SLA during development for sorghum (1) and cowpea (2)	
SLAST(1-2)	the standard specific leaf area of sorghum (1) and cowpea (2)	m^2/g
TA	average daily temperature	°C
TBASE(1-2)	base temperature for the growth and development of sorghum (1) and cowpea (2)	°C
TIINT(1-2)	total intercepted radiation by sorghum (1) and cowpea (2)	MJ/m^2
TMAX1	maximum temperature for the growth and development of sorghum	°C
TOPT1	optimum temperature for the growth and development of sorghum	°C
TORAD	total radiation during simulation	MJ/m2
TORAIN	total amount of rainfall	mm
TOTL(1-3)P	potential uptake of water for transpiration and evaporation from layer 1-3	mm
TOTLAI	total leaf area index	-
TRAN1(1-3)	water uptake for transpiration of sorghum from layer 1-3	mm
TRAN2(1-3)	water uptake for transpiration of cowpea from layer 1-3	mm
TRANL(1-3)	transpiration from layer 1-3	mm
TRANS(1-2)	actual transpiration of sorghum (1) and cowpea (2)	mm
TRAPOT	potential total transpiration	mm
TRPOT(1-2)	potential transpiration of sorghum (1) and cowpea (2)	mm
TRSP(1-2)P	total potential transpiration of sorghum (1) and cowpea (2)	mm
TRSP(1-2)T	total actual transpiration of sorghum (1) and cowpea (2)	mm
TSUM(1-2)	temperature sum of sorghum (1) and cowpea (2)	°Cd
TSUM11, TSUM12	temperature sum needed to complete development of sorghum in the vegetative (1) and generative (2) stage	°Cd
TSUM21, TSUM22	temperature sum needed to complete development of cowpea in the vegetative (1) and generative (2) stage	°Cd
VP	vapour pressure	kPa
WA(1-4)1	amount of water in layer 1-4	mm
WAT	total amount of water in total soil profile	mm
WATE(1-2)T	reduction factor in total transpiration of sorghum and cowpea	-
WATE3T	reduction factor in total evaporation	-

WATER(1-2)	reduction factor for growth rate of sorghum (1) and cowpea (2)	-
WATER3	reduction factor of daily evaporation	-
WLEAF(1-2)	leaf weight of sorghum (1) and cowpea (2)	g/m^2
WN	wind speed	m/s
WP	fractional water content at wilting point	-

Subroutines

Name	description	unit
PERL1	subroutine for calculating percolation from layer 1	
EVA	evaporation	mm
EXTR	extra water available through growth of the roots	mm
FC	field capacity	-
FCW	water amount at field capacity	mm
LAYER	thickness of layer 1	m
PERC	percolation	mm
RAIN	rainfall	mm
TRAN	transpiration	mm
WC1	amount of water in layer 1	mm
PERL2	subroutine for calculating percolation from layer 2-4	
See PERL1 but for layer 2-4		
LAYER	subroutine for calculating the thickness of the three upper layers	
DEEP	deeper rooting depth	m
DEVA	evaporation depth	m
SHAL	shallower rooting depth	m
L(1-3)	thickness of layer 1-3	m
DIST	subroutine for calculating distribution of root depth over the layers	
DEPTH	depth of roots or evaporation	m
FRL(1-3)	fraction roots or evaporation in layer 1-3	-
L(1-3)	thickness of layer 1-3	m
RD(A-B)	rooting depth of crop A and B	m
EXTRA1	subroutine for calculating extra water through root growth of first layer	
DEVA	evaporation depth	m
EVA(1-2)	evaporation of layers 2 and 3	mm
EXTR(1-2)	water available through growth in layer 2 and eventually 3	mm
LAYER(1-2)	thickness of layers 2 and 3	m
RD(A-B)	rooting depth of the two species	m
TRANS(1-2)	transpiration of layers 2 and 3	mm
WA(1-2)	water content of second and third layer	mm
EXTRA2	subroutine for calculating extra water through root growth of second layer	
Same as EXTRA1 but now for layer 3 and 4		
EXTRA3	subroutine for calculating extra water through root growth of third layer	
Same as EXTRA1 but now for layer 4		
PENMAN	subroutine for calculating the potential evaporation and transpiration	
BBRAD	emitted radiation by the crop	$J/m^2/d$
BOLTZM	Boltzman constante	$J/m^2/s/K^{-4}$
DAVTMP	average daily temperature	°C
DEV2	development stage of cowpea	-

DTR	daily radiation	$J/(m^2*d)$
DTRMJ2	see DTR	
IN(1-2)	intercepted radiation by sorghum (1) and cowpea (2)	MJ/m^2
LAI	total leaf area index	-
LAI(1-2)	leaf area index of sorghum (1) and cowpea (2)	-
LHVAP	latent heat of evaporation	J/kg
NRADC	net incoming radiation for the crop	$J/m^2/d$
NRADS	net incoming radiation for the soil	$J/m^2/d$
PENMD	air drying power to remove the vapourised water	$J/m^2/d$
PENMRC	radiation term for evaporising water from the crop	$J/m^2/d$
PENMRS	radiation term for evaporising water from the soi	$J/m^2/d$
PEVAP	potential evaporation	mm
PSYCH	psychrometer constant	kPa
PTRAN(1-2)	potential transpiration; total (-), sorghum (1) and cowpea (2)	mm
RLWN	net outgoing long wave radiation	$J/m^2/d$
SLOPE	tangent of relation between saturated vapour pressure and temperature	kPa/°C
SVP	saturated vapour pressure	kPa
VP	vapour pressure	kPa
WDF	conductance of latent and sensible heat from the surface to the air	$kg/m^2/d/kPa$
WN	wind speed	m/s

Appendix III.
Partitioning of potential evapotranspiration over potential evaporation and potential transpiration

In various models, different methods are used for dividing the potential evapotranspiration over transpiration and evaporation. Below, some of them are illustrated and the choices for the method used in the model are explained. In all methods, the partitioning of evapotranspiration depends on the total crop LAI.
In Sorkam and CERES-Maize, a potential evapotranspiration E_0 is calculated, which is later divided over evaporation and transpiration. The division is given by a set of equations (Xie *et al.*, 2001).

$$E_p = E_0 * (1 - \exp(-LAI)) \qquad 0 \le LAI \le 3$$ equation AIII.1a

$$E_p = E_0 \qquad LAI > 3$$ equation AIII.1b

$$E_s = E_0 * (1 - 0.43 * LAI) \qquad 0 \le LAI \le 1$$ equation AIII.1c

$$E_s = E_0 * \exp(-0.4 * LAI) / 1.1 \qquad LAI > 1$$ equation AIII.1d

If $E_p + E_s > E_0$, then $E_p = E_0 - E_s$

In Lintul2, the calculation of evaporation and transpiration was given by equation AIII.2a,b. In the Lintul2 model, there is no general E_0, but a there is calculated with separate terms for the transpiration and the evaporation.

$$E_p = (PENMRC + PENMD) / LHVAP * (1 - \exp(-0.5 * LAI))$$ equation AIII.2a

$$E_s = (PENMRS + PENMD) / LHVAP * \exp(-0.5 * LAI)$$ equation AIII.2b

In the graph below, the equations are fitted, assuming an E_0 of 5 mm. In Lintul, this means that the radiation term for evaporation of the soil and transpiration of the crop were the same (PENMRS = PENMRC), whereas normally they are slightly different.

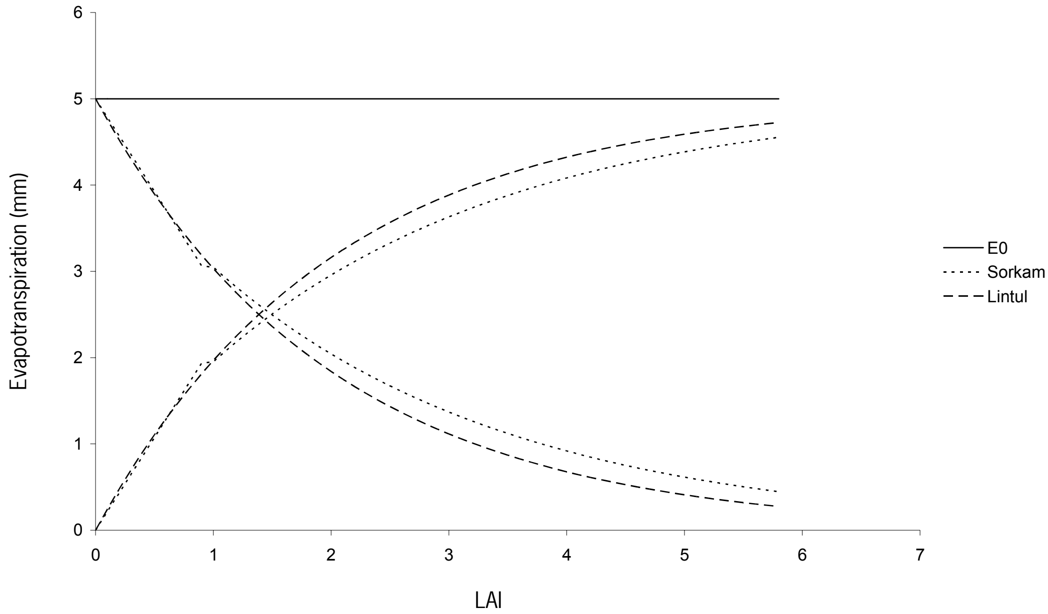

Figure AIII.1. The partitioning of the evapotranspiration over evaporation and transpiration by the different models. The lower set of lines represents the evaporation, the upper set the transpiration.

On deciding which method to use, an aspect which taken into account was the amount of transpiration per kilogram produced biomass. This amount lays in the range of 150-300 kg transpiration/kg biomass (Leffelaar, pers. comm.), depending on the crop. When the developed model was run under the weather circumstances used in the model, the transpiration per kilogram biomass would be 158-172 kg transpiration/kg biomass with the Sorkam method and 144-157 kg transpiration/kg biomass with the Lintul2 method, depending on the crop systems (intercropping, sole sorghum or sole cowpea). Both simulations were done at full rain at the high density. In Sorkam, the potential evapotranspiration was calculated according to

$E_0 = (I_0 + 93) * (TA + 23) / ((150 * (TA + 123))$ (Wegehenkel, 2000), with I_0 the global radiation in J/cm^2

and TA the average daily temperature in degrees Celsius.

These results were on the low side of the range given. Therefore, the method was adjusted and this resulted in the following equations for evaporation and transpiration.

$$E_p = (PENMRC + PENMD) / LHVAP * (1 - \exp(-LAI)) \qquad \text{equation AIII.3a}$$

$$E_s = (PENMRS + PENMD) / LHVAP * \exp(-LAI) \qquad \text{equation AIII.3b}$$

If this was implemented in the model, the amount of transpiration per kilogram biomass was 206-251 kg transpiration/kg biomass, which lays better in the theoretical range. The graph of potential evaporation and potential transpiration against LAI at E_0 = 5 mm is shown below.

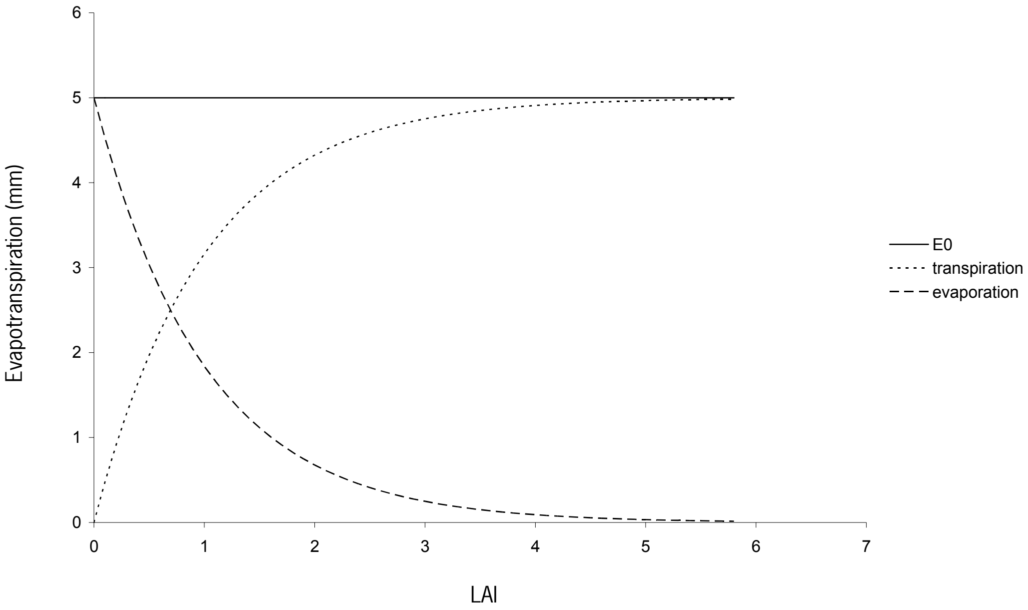

Figure AIII.2. The partitioning of the evapotranspiration over evaporation and transpiration in the developed model.

Appendix IV.
Results for the yields of chapter 6

Table AIV.1 The yields of sorghum and cowpea in pure stand and in intercrop when changes were made in plant properties or agronomic management.

change from reference	cropping system	crop	density (plants/m^2)	water supply level (% of normal rain) 100	75	50	25
height of sorghum	pure stand	sorghum	4	232	223	215	143
			8	290	282	272	162
		cowpea	8	115	109	97	61
			16	160	154	142	94
	intercrop	sorghum	8	227	221	218	140
		cowpea	16	82	81	75	47
		sorghum	8	252	245	240	150
		cowpea	8	51	50	45	27
		sorghum	4	186	180	177	128
		cowpea	8	69	68	61	37
higher LUE cowpea (2.0 g/MJ PAR)	pure stand	sorghum	4	232	223	215	143
			8	290	282	272	162
		cowpea	8	168	161	146	92
			16	217	210	196	131
	intercrop	sorghum	8	231	224	220	138
		cowpea	16	104	104	98	63
		sorghum	8	252	245	239	147
		cowpea	8	71	70	64	40
		sorghum	4	185	179	176	124
		cowpea	8	99	97	88	55
later planting of sorghum	pure stand	sorghum	4	241	238	222	116
			8	296	293	273	126
		cowpea	8	115	109	97	61
			16	160	154	142	94
	intercrop	sorghum	8	229	233	222	109
		cowpea	16	110	101	91	45
		sorghum	8	254	256	241	117
		cowpea	8	74	67	59	27
		sorghum	4	191	194	186	106
		cowpea	8	93	83	73	33
higher density	pure stand	sorghum	16	340	333	321	175
			24	365	359	345	179
		cowpea	32	202	197	187	128
	intercrop	sorghum	24	323	317	305	159
		cowpea	32	53	54	52	33
		sorghum	16	288	281	272	151
		cowpea	32	70	71	68	45
rain evenly distributed	pure stand	sorghum	4	242	235	222	157
			8	299	293	278	167
		cowpea	8	139	137	138	55
			16	184	182	183	80
	intercrop	sorghum	8	245	239	223	157
		cowpea	16	83	83	84	24
		sorghum	8	265	259	243	162
		cowpea	8	54	55	55	15
		sorghum	4	200	194	180	148
		cowpea	8	77	77	78	23