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GROWTH AND YIELD OF MILLET AND COWPEA IN RELAY AND INTERCROP SYSTEMS IN THE SAHELIAN ZONE IN YEARS WHEN THE ONSET OF THE RAINY SEASON IS EARLY

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SUMMARY

Field trials conducted previously in Niger have shown that in years when the onset of the rains is 15–20 days earlier than average, the long growing season can be exploited by growing a relay crop of millet (*Pennisetum glaucum*) and cowpea (*Vigna unguiculata*). In the trials reported here, the advantages of relay cropping were compared with intercropping with improved management and intercropping under traditional management during the 1989, 1990 and 1991 rainy seasons at the ICRISAT Sahelian Center, Sadore, Niger. The length of the growing season varied from 139 to 150 days over the three seasons. The relay crop produced more dry matter and leaf area and yielded more than the intercrops in all three years, confirming that in years when the onset of the rains is early, relay cropping with millet and cowpea is a better option than growing the same two species as an intercrop. Relay cropping avoids the competitive effects inherent in intercropping systems, while offering the additional advantages of rotating cereals with legumes.

Mijo y caupí en sistemas de relevo y de cultivo simultáneo

RESUMEN

Los ensayos de campo llevados a cabo con anterioridad en Nigeria demostraron que en los años en que las precipitaciones se inician 15–20 días antes que el promedio, la estación prolongada de cultivo puede explotarse mediante el cultivo de relevo de mijo (*Pennisetum glaucum*) y caupí (*Vigna unguiculata*). En los ensayos aquí relatados, se compararon las ventajas del cultivo de relevo con las del cultivo simultáneo con manejo mejorado, y con las del cultivo simultáneo con manejo tradicional, durante las estaciones de lluvias de 1989, 1990, y 1991, en el ICRISAT Sahelian Centre, en Sadora, Niger. La duracíon de la estación de crecimiento presentó una variación de 139 a 150 días a lo largo de las tres temporadas. El cultivo de relevo produjo una mayor cantidad de materia seca y superficie de hoja, al igual que un mayor rendimiento que el cultivo simultáneo durante los tres años, confirmando así que en los años con temprano inicio de las lluvias, el cultivo de relevo con mijo y caupí constituye una mejor opción que el cultivo de las mismas dos especies en forma simultánea. El cultivo de relevo evita los efectos competitivos inherentes a los sistemas de cultivo simultáneo, ofreciendo a la vez la ventaja adicional de la rotación entre cereales y legumbres.

INTRODUCTION

A large temporal variability in the rainfall received over the past two decades in West Africa has resulted in considerable instability in crop yields. Although the

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existence of long term trends is uncertain, it is clear from rainfall records that regions immediately south of the Sahara experience extended periods of both high and low rainfall (Farmer and Wigley, 1985). Under the increasing demographic and ecological pressures in the southern Sahelian zone, the traditional systems of crop production are unable to meet the people's needs. Ensuring some degree of yield stability for the farmers who face increasing climatic risks has become a priority for the national governments and the research institutions in the region.

Clearly, even in the highly variable rainfall environment of the southern Sahelian zone, years with good rainfall (characterized by an early to normal onset of the rains and fairly good rainfall distribution) do occur and farmers must exploit them fully to ensure that any stored soil water from rainfall in good years is retained for use by crops in the following year. This is one way of ensuring food security when there are good and bad rainfall years. The need for such a strategy is greatest on the sandy soils of the southern Sahelian zone, which have a poor water holding capacity and suffer high rates of evaporative loss.

In practical terms, however, the question arises as to how the farmers are to foretell whether or not the coming rainy season is likely to be favorable. The problems currently associated with accurate weather forecasting for West Africa are well documented (Farmer and Wigley, 1985). Hence recent efforts have been devoted to predicting the essential characteristics of the approaching rainy season and matching the crop decisions to the expected rainfall (Sivakumar, 1988; Stewart, 1989).

From an analysis of long term daily rainfall data for several locations in West Africa, Sivakumar (1988) has shown that rainy season potential can be predicted and exploited from a knowledge of the relation between the date of onset of the rains and the length of the growing season. He defined the date of onset of the rains as the date after 1 May when at least 20 mm of rainfall has accumulated over three consecutive days with no dry spell of more than seven days within the next 30 days. Stewart (1989) has shown that the duration of the rainy season at Niamey in Niger can be reliably predicted from the date of onset of the rains and has suggested that detailed crop-specific farm-level recommendations must be based on more rigorous research. Using the daily rainfall data from 1961 to 1990, Sivakumar *et al.* (1992) calculated that the average length of the growing season in Niamey is 109 days. They calculated that if the onset of the rains is early, there is an 88% probability that the growing season will exceed 110 days and a 49% probability that it will exceed 130 days. In field trials in Niger during 1986 and 1987, Sivakumar (1990) showed that in years when the onset of the rains was early, the long growing season could be exploited by growing a relay crop of cowpea for hay after the first crop of short duration (90–100 days) millet.

The practice of growing a short duration, fast growing secondary crop, usually a legume, after the principal cereal crop, is a strategy well known to the farmers in tropical regions, especially in Asia. Relay cropping is common in the medium to high rainfall regions of India, especially on the heavier soils with a good water holding capacity, although it is uncommon in low rainfall regions on sandy soils with a poor water holding capacity. Relay cropping was first proposed as a strategy to exploit good years on the sandy soils of the southern Sahelian zone by Sivakumar (1990). However, questions still remained concerning the relative advantage offered by the relay crop compared with the traditional practice of intercropping long season millet with cowpea. Intercropping is used by Sahelian farmers to minimize risks and spread labour peaks (Norman, 1974; Matlon, 1980). It enables them to spread the risk over two contrasting crops and also to exploit the long rainy season during a good year. However, yields of intercropped millet are less than those of sole millet since they are affected by factors such as planting density, plant population, planting dates and the spatial arrangement of the component crops (Fussell and Serafini, 1985; Ntare *et al.*, 1989). Hence, where the farmers' main aim is to harvest a full crop of millet and any additional cowpea hay is a bonus, the millet-cowpea relay crop may offer advantages.

The objective of the present study was to compare the performance of relay cropped millet and cowpea with a millet/cowpea intercrop under both improved and traditional management during years when the onset of the rains is early. Since the onset of the rains is variable from year to year, the trials were designed to run for long enough to include at least three years when the rains began early. It so happened that the onset of the rains was early during the first three years (1989–1991) and hence early evaluation of the trials was possible.

MATERIALS AND METHODS

The experiment was conducted during the rainy seasons of 1989–91 at the ICRISAT Sahelian Center, Sadore (13°15′N, 2°17′E), 45 km south of Niamey, Niger. The soil of the experimental site is classified as a sandy, siliceous, isohyperthermic Psammentic Paleustalf with 91% sand, 5% silt and 4% clay in the A horizon (West *et al.*, 1984). The soil has a pH of 4.9, a cation exchange capacity of 1.3 meq 100 g^{-1} and a base saturation of 41.9%.

The data discussed in this paper are taken from a large experiment sown in a randomized block design with six replications. The treatments described here are the millet–cowpea relay crop, the improved intercrop of short duration millet with cowpea, and the traditional long duration millet and cowpea intercrop. It was necessary to include the two intercrop systems because the traditional intercrop system cannot be compared directly with the relay crop since it uses long duration varieties that are planted on flat soil with no fertilizer. The relay crop system is only possible when farmers adopt improved short duration millet cultivars so that the relay crop of cowpea gets a reasonably long growing season, at least for the production of hay (Sivakumar, 1990). Both the relay and the improved millet/cowpea intercrop systems incorporate the use of improved, short duration varieties of millet and cowpea at high densities, the use of a limited amount of fertilizer, and ridging. Details of the varieties used, and the sowing and harvest dates for the three cropping systems over the three years are shown in Table 1.

During each year 45 kg P_2O_5 ha^{-1}, as single superphosphate, was supplied as a basal application to the relay and improved intercrop treatments at the time of land preparation before the millet was sown. Calcium ammonium nitrate was applied to the millet at 21 and 45 days after planting to supply a total of 45 kg N ha^{-1}. This schedule of fertilizer application was the one recommended for millet and cowpea crops grown on the sandy soil of the Sahelian region. No fertilizer was applied to the cowpea in either the relay or the intercrop treatments. The traditional intercrop treatment received no fertilizer since most Sahelian farmers do not apply fertilizer to millet.

In the relay crop, millet was sown in pockets spaced 80 cm apart along ridges 75 cm apart, and later thinned to two plants to a pocket, giving a plant population of 33 333 plants ha^{-1}. The relay cowpea crop was sown into the millet several days before the millet harvest after at least 10–15 mm of rain had fallen, to ensure good establishment. The relay cowpea crop was sown 18 days before the millet harvest in 1989 and 1991 but only 10 days before it in 1990 because the rainfall until then was inadequate. Since the relay cowpea was grown mainly for hay and so ideally should be densely planted, the cowpea was sown in pockets 40 cm apart between the millet rows both on the ridge and in the furrow, giving an effective spacing of 40 × 37.5 cm. After establishment, the relay cowpea was thinned to two plants per pocket, giving a density of 133 333 plants ha^{-1}. After the millet harvest, the millet stalks were spread between the cowpea rows as a mulch to conserve soil moisture.

In the improved intercrop, the millet was sown in pockets 1.33 m apart on ridges 75 cm wide. After establishment the millet was thinned to three plants per pocket to give a final density of 30 075 plants ha^{-1}. The wider between-pocket spacing on the ridges in the intercrop was used to accommodate the cowpea. The cowpea density in the intercrop was 20 050 plants ha^{-1}.

In the traditional intercrop, the millet was sown on flat soil in rows, following the farmers' traditional practice. A variable spacing was used, since the farmer

Table 1. *Variety used, and sowing and harvest dates for the three cropping systems during the 1989, 1990 and 1991 rainy seasons*

Variety		Millet Sowing			Millet Harvest			Cowpea Sowing			Cowpea Harvest		
Millet	Cowpea	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991
Millet–cowpea relay crop													
CIVT	TN 5-78	20 May	23 May	26 May	5 Sep.	3 Sep.	27 Aug.	18 Aug.	25 Aug.	9 Aug.	17 Oct.	19 Oct.	12 Oct.
Millet/cowpea improved intercrop													
CIVT	TN 5-78	20 May	23 May	26 May	5 Sep.	3 Sep.	27 Aug.	30 Jun.	25 Jun.	13 Jun.	14 Sep.	13 Sep.	11 Sep.
Millet/cowpea traditional intercrop													
Sadore Local	Sadore Local	20 May	23 May	26 May	15 Sep.	12 Sep.	15 Sep.	30 Jun.	25 Jun.	13 Jun.	17 Oct.	12 Oct.	12 Oct.

sows the millet using a long hoe to open up holes as he walks. Hence the row configuration was irregular, but measurements at harvest showed a plant density of approximately 17 340 plants ha^{-1}. Cowpea was only sown in alternate rows, resulting in a low plant population of approximately 15 000 plants ha^{-1}.

Growth measurements in the millet crop were made by sampling two pockets in each replicate at 7–10 day intervals, preserving a guard area around the sampling area. The plant samples were separated into individual components: leaves, stems and heads. Leaf area was measured with a leaf area meter (LI-COR Ltd., Lincoln, Nebraska, USA). Plant components were dried to constant weight at 65°C and then weighed. Final yields were estimated from an area of 25 m^2.

RESULTS

Rainfall and length of growing season

In all three years (Fig. 1), the onset of the rains was early (20 May 1989, 23 May 1990 and 26 May 1991) relative to the mean date of onset calculated from long term rainfall data (12 June, Sivakumar, 1990).

When the rains start early, the growing season usually stretches over 120 days as opposed to 100 days after the normal onset of the rains. Although the onset of rains was early in all three seasons, total rainfall was variable (623 mm in 1989, 400 mm in 1990 and 603 mm in 1991). In 1989, the rains continued until 9 October and the growing season, taking into account residual soil moisture, extended to 17 October, giving a total growing season of 150 days for the relay crop (Tables 1 and 2). In 1990, the length of the growing season was similar, 149 days. In 1991, although the rains continued until 4 October, an 18-day dry spell from 12 to 30 September reduced soil moisture storage in the profile and shortened the growing season to 139 days.

Dry matter accumulation

Although the total seasonal rainfall during 1989 was 623 mm, there were two long dry spells during the growing season: a 23-day dry spell after the millet was sown and a 14-day dry spell in July (Fig. 1). These dry spells affected the early growth of the millet and intercrop cowpea. However, with the long growing season, the cowpea relay crop was little affected and its dry matter accumulation was greater than that of the improved intercrop (Fig. 2).

There was little difference between the relay and the intercrop in the dry matter accumulated in leaves and stems in 1989. However, dry matter accumulation in the heads (shown as the area between the stem and total dry matter curves) was higher for the relay crop than for the intercrop (Fig. 2). The period of rapid dry matter accumulation in the heads in the intercropped millet coincided with that in the cowpea and dry matter accumulation may therefore have been affected by competition for resources at that time.

Dry spells during the 1989 rainy season resulted in a lower total dry matter production by millet than in 1990. The total dry matter (at final sampling)

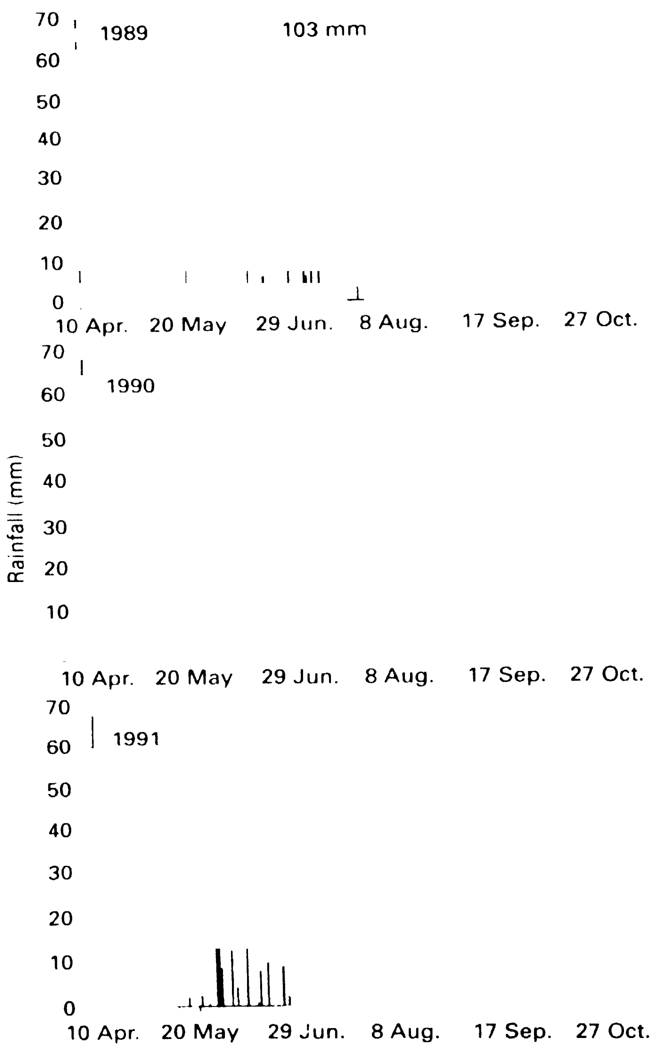

Fig. 1. Rainfall patterns during the 1989, 1990 and 1991 rainy seasons at the ICRISAT Sahelian Cent Sadore, Niger.

Table 2. *Length of the growing season (days) for the three cropping systems during the 1989, 1990 and 1991 rainy seasons*

	Length of growing season		
	1989	1990	1991
Millet – cowpea relay crop	150	149	139
Millet/cowpea improved intercrop	117	113	108
Millet/cowpea traditional intercrop	150	149	139

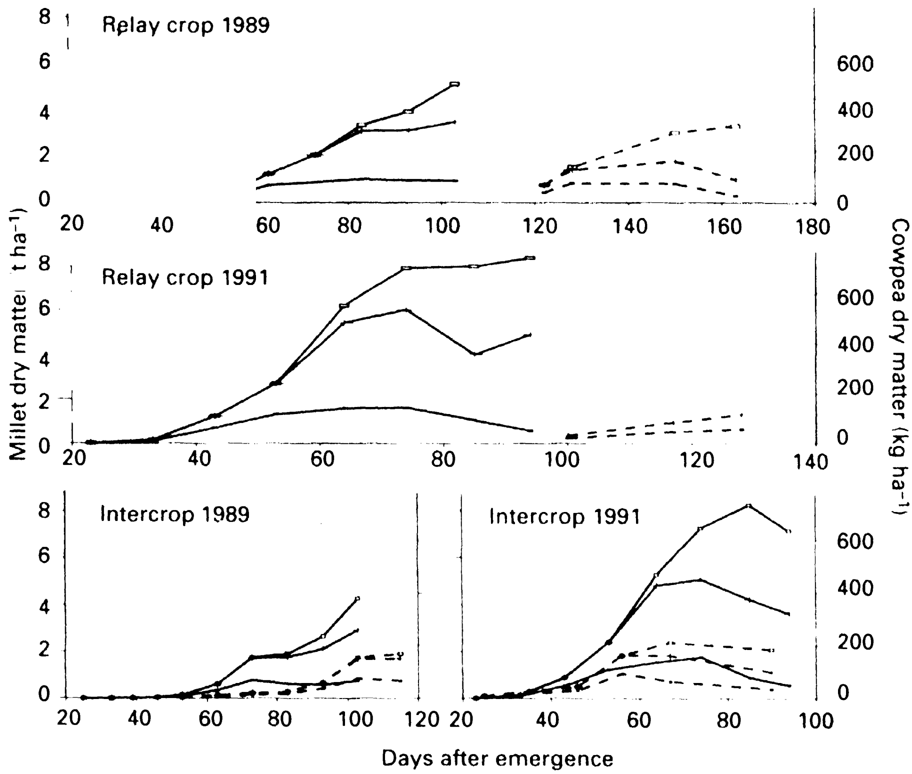

Fig. 2. Dry matter distribution in plant components (leaf, □; stem, +; total, □) of millet (—) and cowpea (---) in the relay and improved intercrop during the 1989 and 1991 rainy seasons at the ICRISAT Sahelian Center, Sadore, Niger.

accumulated by the relay crop in 1989 was 5.1 t ha^{-1}, compared with 6.0 t ha^{-1} in 1990. Improved intercrop millet produced 4.3 t ha^{-1} in 1989, compared with 5.1 t ha^{-1} in 1990. Regular rainfall up to 21 September helped the vegetative growth of the relay cowpea crop, which produced 0.45 t ha^{-1} total dry matter in 1989.

With a more favourable rainfall distribution, dry matter accumulation in both the relay crop and the intercrop was higher in 1991 than in 1989 (Fig. 2). There was a rapid accumulation of dry matter in the relay millet crop between 40 and 75 days after sowing (DAS), producing a total dry matter yield of 7.91 t ha^{-1}. In contrast with the 1989 rainy season, in 1991 the intercrop cowpea (sown 18 days after millet) had passed its most rapid period of dry matter accumulation by 60 DAS and hence did not compete with the intercrop millet while the millet heads were growing.

Leaf area index

The leaf area index of the relay millet crop was greater than that of the two intercrops in all three years (Fig. 3). The wide rows used for millet in the improved intercrop left much of the soil surface exposed and the crop did not cover the ground effectively. Under sparse crops, soil evaporative losses increase, resulting

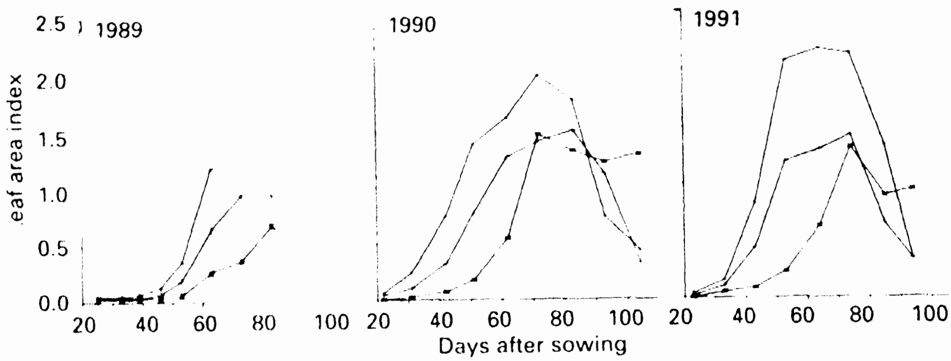

Fig. 3. Leaf area index of millet in the relay (□), improved intercrop (+) and traditional intercrop (*) during the 1989, 1990 and 1991 rainy seasons at the ICRISAT Sahelian Center, Sadore, Niger.

in poor water use efficiency (Wallace, 1991; Wallace *et al.*, 1992). In the traditional intercrop, the low plant density and wide row configuration resulted in the lowest leaf area index of the three treatments.

Grain and hay yields

The grain yields of the relay millet crop were larger than those of the intercrop millet in all three years, and especially in 1991, which had the best rainfall distribution (Table 3). The hay yields of the relay cowpea were also better than those of the improved intercrop in all three years, but cowpea seed yields were poor, confirming the findings of Ntare (1990) and Reddy *et al.* (1990). Regular rainfall up to 21 September promoted vegetative growth in the relay cowpea crop in 1990. However, the 19-day dry spell after 21 September affected pod filling, hence the seed yield of the relay cowpea crop was very low in 1990. The seed and

Table 3. *Grain and hay yields (t ha^{-1}) for the three cropping systems in the 1989, 1990 and 1991 rainy seasons*

	Grain/seed†			Straw/hay		
	1989	1990	1991	1989	1990	1991
			Millet			
Relay crop	1.23	1.66	2.09	2.18	3.53	4.13
Improved intercrop	0.96	1.25	1.36	2.48	2.27	2.63
Traditional intercrop	0.96	0.26	0.68	2.10	3.78	1.27
SE (±)	0.11	0.13	0.17	0.30	0.37	0.35
			Cowpea			
Relay crop	0.13	0.04	0.15	0.26	0.24	0.30
Improved intercrop	0.09	0.00	0.10	0.10	0.02	0.18
Traditional intercrop	0.18	0.01	0.07	0.30	0.04	0.28
SE (±)	—	—	—	0.037	0.017	0.05

†SE for cowpea seed has not been presented because of the generally low yields and high variability.

hay yields of the traditional intercrop were larger in 1989 than in the other years because of the longer growing season.

DISCUSSION

The results confirm that the advantage of early rains and a longer growing season in the southern Sahelian zone can be better exploited by relay cropping millet and cowpea than by intercropping. In both 1990 and 1991 the growing season was shorter than the upper limit of 154 days noted by Stewart (1989) from a 30-year rainfall record for Niamey from 1954 to 1989. The relation between yield and growing season length (139 to 150 days) in the relay crop and the traditional intercrop for the three years of these trials (Table 1) suggests that cowpea and millet can benefit from longer growing seasons.

The millet relay crop is effectively the same as a sole crop and hence avoids the competitive effects of cowpea in the intercrop system. As reported from previous studies in the Sahelian zone (Ntare *et al.*, 1989), the date of sowing of the cowpea relative to the millet in the intercrop affects the extent of complementarity in the growth patterns of these two crops. In both 1989 and 1990, sowing of cowpea into the intercrop was delayed until sufficient rain fell in late June and this clearly resulted in the suppression of cowpea growth by the millet. In 1989, the intercropped cowpea accumulated more dry matter after plentiful rainfall in August, although this period coincided with the growth of millet heads.

Rainfall in June, July and August 1990 (51, 104 and 99 mm, respectively) was less than the long term means (76, 143 and 192 mm as reported by Sivakumar, 1986). Crop growth was particularly affected by the moisture deficit in August. The intercrop cowpea was a failure in 1990 because of the delay in planting; competition from the early vigorous growth of the millet and a nine day dry spell after the cowpea was sown resulted in poor cowpea establishment and reduced vigour.

Dry matter accumulation per unit area was high in the millet grown as a relay crop because of the higher density of plants compared with the intercrop millet, which was spaced to accommodate the intercrop cowpea between the rows. The relay cowpea was also densely sown since it was grown mainly for its hay. One general concern in the Sahel is that increased plant densities mean increased use of soil water, thus increasing the risk of crop failure from drought. However, an early onset of the rains is generally associated with a higher total rainfall. Stewart (1989) showed that for Niamey, the median rainfall amount is 22% higher for early seasons than the median for all seasons. Also, after the millet harvest, rainfall in August and September is generally sufficient for the establishment and early growth of a high density relay cowpea crop, allowing reasonable hay yields.

The relay millet crop outyielded the intercropped millet because relay cropping avoids the competitive effects inherent in the planting density, plant population, planting dates and spatial arrangement of the component crops in an intercrop system. However, one problem with the early onset of rains is the incidence of millet pests, particularly the earhead caterpillar, *Raghuva albipunctella* De Joannis. Nwanze and Sivakumar (1990) reported that the onset and continuity of the rains, and favourable soil moisture and temperature conditions are key factors in termination of diapause, duration of post-diapause development and adult emergence. The level of crop infestation depends on the extent of synchronization of the occurrence of the adult moths with the period of panicle exsertion in the millet, since this is the physiological growth stage preferred by ovipositing females. Nwanze and Sivakumar (1990) emphasized the need to collect data over several years in order to quantify the major factors required to develop agroecosystem models as a basis for designing integrated pest management strategies.

Even though the plant densities in the traditional intercrop system were low, hay yields of the cowpea were higher in this system than those of the improved intercrop because the traditional cowpea cultivar, Sadore Local, is a highly vegetative, photoperiod-sensitive, spreading type that benefits from a long growing season and produces higher hay yields than the improved cowpea cultivars (Ntare, 1990).

Our results confirm that in years when the rains begin early, relay cropping offers advantages over intercropping; it is possible to establish a sole relay crop of cowpea that can provide hay and benefit the millet crop in the following year. In view of the increasing trend towards the continuous cultivation of millet with no intervening fallow period this residual benefit merits serious consideration since it may improve the sustainability of millet production systems in the southern Sahelian zone. In this fragile ecosystem, the importance of crop rotations to restore soil fertility and maintain productivity is receiving increased attention. Analysis of rainfall data in Senegal and Mali shows that there is also considerable potential for relay cropping in these countries, as there is a greater likelihood of an early onset of the rains in the Sudanian climatic zone than in the Sahelian zone (Sivakumar, 1988; Gueye and Sivakumar, 1992; Tekete *et al.*, 1992).

Note. Mention of a proprietary product in this paper does not imply endorsement or preference by ICRISAT over another product of a similar nature.

REFERENCES

Farmer, G., & Wigley, T. M. L. (1985). *Climatic Trends for Tropical Africa.* Norwich, England: University of East Anglia.

Fussell, L. K. & Serafini, P. G. (1985). Crop associations in the semi-arid tropics of West Africa: research strategies past and future. In *Appropriate Technologies for Farmers in Semi-arid West Africa,* 218–235. (Eds H. W. Ohm and J. G. Nagy). Indiana, USA: Purdue University.

Gueye, M. & Sivakumar, M. V. K. (1992). Analyse de la longueur de la saison culturale en fonction de la date de debut des pluies au Senegal. Compte rendu des Travaux No. 2. Niamey, Niger: Centre Sahelien de l'ICRISAT.

Matlon, P. J. (1980). Local varieties, planting strategies, and early season farming activities in two villages in Central Upper Volta. ICRISAT West Africa Economics Program Progress Report 2. Ouagadougou, Burkina Faso: International Crops Research Institute for the Semi-Arid Tropics.

Norman, D. W. (1974). Rationalizing mixed cropping under indigenous conditions. The example of Northern Nigeria. *Journal of Development Studies* 11:3–21.

Ntare, B. R., Serafini, P. G. & Fussell, L. K. (1989). Recent developments in millet/cowpea cropping systems for low rainfall areas of the Sudano-Sahelian zone of West Africa. In *Soil, Crop and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone: Proceedings of the International Workshop*, 11–16 January 1987. Niamey, Niger: International Crops Research Institute for the Semi-Arid Tropics.

Ntare, B. R. (1990). Intercropping morphologically different cowpeas with pearl millet in a short season environment in the Sahel. *Experimental Agriculture* 26:41–47.

Nwanze, K. F. & Sivakumar, M. V. K. (1990). Insect pests of pearl millet in Sahelian West Africa – II. *Raghuva albipunctella* De Joannis (Noctuidae, Lepidoptera): distribution, population dynamics and assessment of crop damage. *Tropical Pest Management* 36:59–65.

Reddy, K. C., Van Der Ploeg, J. & Maga, I. (1990). Genotype effects in millet/cowpea intercropping in the semi-arid tropics of Niger. *Experimental Agriculture* 26:387–396.

Sivakumar, M. V. K. (1986). Climate of Niamey. Progress Report 1. Niamey, Niger: ICRISAT Sahelian Center.

Sivakumar, M. V. K. (1988). Predicting rainy season potential from the onset of rains in southern Sahelian and Sudanian climatic zones of West Africa. *Agricultural and Forest Meteorology* 42:295–305.

Sivakumar, M. V. K. (1990). Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. *Agricultural and Forest Meteorology* 51:321–332.

Sivakumar, M. V. K., Maidoukia, A. & Stern, R. D. (1992). *Agroclimatology of West Africa: Niger. (Second Edition). Information Bulletin No. 5.* Patancheru, India: International Crops Research Institute for the Semi-Arid Tropics.

Stewart, J. I. (1989). Potential for response farming in sub-Saharan Africa. In *Soil, Crop and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone: proceedings of the International Workshop*, 255–264. Niamey, Niger: International Crops Research Institute for the Semi-Arid Tropics.

Tekete, A., Sivakumar, M. V. K. & Diarra, B. (1992). Analyse de la longueur de la saison culturale en fonction de la date de debut des pluies au Mali. Compte Rendu des Travaux No. 3. Niamey, Niger: Centre Sahelien de l'ICRISAT.

Wallace, J. S. (1991). The measurement and modelling of evaporation from semi-arid land. In *Soil Water Balance in the Sudano-Sahelian Zone, IAHS Publication No. 199*, 131–148 (Eds M. V. K. Sivakumar, J. S. Wallace, C. Renard and C. Giroux). Wallingford, UK: International Association for Hydrological Sciences.

Wallace, J. S., Lloyd, C. R. & Sivakumar, M. V. K. (1992). Measurement of soil, plant and total evaporation from millet in Niger. *Agricultural and Forest Meteorology* (In Press).

West, L. T., Wilding, L. P., Landeck, J. K. & Calhoun, F. G. (1984). Soil Survey of the ICRISAT Sahelian Center, Niger, West Africa. Texas, USA: Soil and Crop Sciences Department, TROPSOILS, Texas A & M University, College Station.