

Full Length Research Paper

# Effects of variety and row spacing on radiation interception, partitioning of dry matter and seed set efficiency in late season sunflower (*Helianthus annuus* L.) in a humid zone of Nigeria

Agele, S. O.<sup>1\*</sup>, Maraiyesa, I. O.<sup>2</sup> and Adeniji, I. A<sup>2</sup>

<sup>1</sup>Department of Crop, Soil and Pest Management, Federal University of Technology, Akure, Nigeria.

<sup>2</sup>ARMREC, University of Agriculture, Abeokuta, Nigeria.

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In the tropics, crops sown in the late season are subjected to concurrent stresses of high air and soil temperatures, large saturation vapour pressure deficits and negligible soil water regimes. The responses of three sunflower cultivars to row spacing was analysed in terms of radiation interception and use, plant to plant variability, biomass accumulation and seed set efficiency during the late seasons of 2002 and 2003 on the field in Akure, a rainforest zone of Nigeria. Sunflower cultivars (*Functua* local, Record and Isaanka) were cropped at 90 x 30, 90 x 60 and 60 x 30 cm row spacing corresponding to 37,037, 18,519 and 55,555 plant.m<sup>-2</sup>. Increasing density of plant stand appeared to have promoted differences in resource availability per plant during growing season. Row spacing did not significantly affect IPAR while the effects of spacing and cultivar were similar on RUE. Leaf area and dry matter accumulation are suboptimal but RUE appeared to be conservative in circumstances of high saturation vapour pressure deficit and soil moisture stress of the late season. Crops in wide rows intercepted less radiation than their counterparts in narrow rows, and yield response to narrow rows was significant in all cultivars. Seed yield/ha increased as plant density increased although yield of the individual plants and their components were significantly reduced. Among the cultivars, differences in the growth of individual plant at different intensities of inter plant competition were obtained, narrow row spacing enhanced plant-plant variability (inter-plant variation). Under the limiting soil water situation enhanced soil temperatures of the late season EF relates to plant biomass ( $r^2 > 0.70$ ), dry matter relates to accumulated intercepted radiation IPAR ( $r^2 > 0.90$ ) and fractional intercepted radiation (fIPAR) relates to seed yield ( $r^2 > 0.95$ ) while fIPAR is a function of thermal time (TT) ( $r^2 > 0.80$ ).

**Key words:** Sunflower, cultivars, late season, RUE, extinction coefficient, plant-plant variability, dry matter partitioning, seed set, seed yield.

## INTRODUCTION

Sunflower, *Helianthus annuus*, L, is an important oil crop worldwide, and in the tropics, its cultivation is becoming widespread. Sunflower combines high yield with great adaptation capacity, the characteristically high photosynthetic capacity and HI makes this crop viable for contrasting environments. The post rainy season period offers a unique cropping opportunity for sunflower in the humid zone of Nigeria (Ogunremi, 1988; Fagbamigbe and Ade-

oye, 1999; Agele et al., 2002). However, the post rainy season is characterized by concurrent stresses due to extremely high soil and air temperatures, solar intensity and vapour pressure deficits (atmospheric dryness) and severe soil moisture deficits. Soil water reserve is a valuable resource important to the exploitation of the potentials offered by the post rainy season cropping period (Agele, 2003). Row spacing is a cultural practice that may modify resource availability per plant. This practice may influence the ability of each plant to allocate to the ear/head minimum assimilate requirement for seed set (Egli, 1998; Vega et al., 2001).

\*Corresponding author. E-mail: [ohiagele@yahoo.com](mailto:ohiagele@yahoo.com).

Reduced plant biomass and increased plant-to-plant variability are expected responses to crowding in monocultures (Maddonni and Otegui, 2004). A plant population threshold that maximizes grain yield is proposed while substantial increase in barrenness at plant population beyond this threshold has been proposed (Tetio-Kagho and Gardner, 1988). Responses to increased stand density in crops are enhanced inter-plant competition and variability in phenotypic traits such as biomass, height, kernel number etc. Improved performance at high stand density may be through high photosynthesis and LAI, and reduced plant barrenness (Sangoi et al., 2002). Related to this are traits like compact canopy architecture (shorter plants), and a more balanced allometric relationship between the head and the seeds, in addition to improved biomass partitioning from vegetative to reproductive structures (Egli, 1998; Vega et al., 2001). The knowledge of plant physiological responses at high plant populations is important for improving crop simulation models aimed at predicting KNP (Ritchie and Alargarswamy, 2003). Density induced competition for assimilates or assimilate limitation during seed filling could cause kernel abortion due to low dry matter partitioning to reproductive sinks at flowering (Gardner and Gardner, 1983; Vega et al., 2001; Pressman et al., 2002; Maddonni and Otegui, 2004).

In plants, the responses to crowding include plant elongation (height of growth) and leaf reorientation (Maddonni et al., 2001). However, delayed onset of intra-specific competition and a more uniform growth of individual plants within a stand will increase light attenuation / perception. The adaptation of leaf azimuth distribution to planting pattern (canopy behaviour), has a significant effect on light interception. Delayed onset of intra-specific competition and a more uniform growth of individual plants within a stand will increase light attenuation / perception. Leaf positioning (orientation) within the canopy (uppermost stratum) adaptation of leaf azimuth distribution to planting pattern (canopy behaviour), has a significant effect on light interception (Maddonni et al., 1999). This feature could help to develop shade avoidance characteristics (Maddonni et al., 2001). Enhanced perception of light environment may increase ability for resource capture and the sensitivity of individual plant within a monoculture. The interaction effect between canopy behaviour and plant spatial arrangement on light interception is reported (Maddonni et al., 1999). Leaf re-orientation is seen as a reaction so as to colonize empty spaces or to minimize interference (Girardin and Tollenaar, 1994). The plasticity of a crop canopy based on leaf re-orientation would contribute to maintain a daily light interception nearly independent of inter-row distance. The ability of maize leaves to undergo spatial re-orientation determined a similar K value under variable stand densities (Maddonni et al., 2001). It is necessary to understand biological processes responsible for leaf re-orientation and other plant behavior under competition in diverse crop species and agroecologies.

Charles-Edwards (1984), Egli (1998) and Ball et al. (2002) proposed that each reproductive structure requires a minimum rate of assimilate supply during its initial development to sustain growth.  $SNP = PGRc P_R \lambda^{-1}$ . This proposition emphasizes the role of carbon as an energy source and its adequacy to integrate effects of other resources (Vega et al., 2003). The partitioning of biomass to seed is important to yield in crops including oilseed crops. Its physiological regulation is poorly understood (Vega et al., 2003). Radiation use efficiency (radiation conversion coefficients) provides basis for understanding environmental influences on crop productivity (Gillet et al., 2001). Variability of RUE is controlled by biological processes of phenology, leaf N content and CO<sub>2</sub> exchange rates (Sinclair and Horie, 1989) and physical factors are due to weather variables mainly saturation vapour pressure deficit, drought index and temperature (Monteith, 1989; Calvino et al., 2004). Radiation conversion coefficient (E) which ranges from 1.2–1.7 g dm/MJ for most crops is affected by temperature (Takami et al., 2002). High temperatures aggravate the effects of drought stress on crops; it decreases RUE and dry matter accumulation possibly due to increased loss of photosynthates via respiration.

The responses of three sunflower cultivars to row spacing in the late cropping season in a humid tropical rain-forest environment was analysed on the field in terms of radiation interception and use, plant to plant variability, biomass accumulation and seed set efficiency

## MATERIALS AND METHODS

### Experimental site

The field experiments were conducted in the early season of 2002 and 2003 at the Teaching and Research Farm of the University of Agriculture, Abeokuta (7° 15'N, 3° 25'E, 140 m above sea level) in South West Nigeria. The soil is sedentary, deep and well drained and was derived from basement complex (FDALR, 1985). Other soil characteristics at the site of the experiment are shown in Table 1. The trials each year consisted of 3 x 3 factorial combinations of sunflower cultivars and row spacing which were replicated three times in a Randomized complete Block Design. The sunflower varieties were Functua local, Record and Isaanka which were obtained from the Institute of Agricultural Research, Zaria. Row spacing consisted of 90 x 30, 60 x 30 and 60 x 30 cm, which correspondent to 37,037; 18,519; 55,555 plant/ha respectively. The site of the experiment were manually cleared of fallow vegetation after which seeds of sunflower varieties were planted on the field plots. The first trial was established in June, 2002 while the second trial was established in June, 2003 following the procedure for 2002 experiment. Seeds were dressed with apron plus before planting and were planted at two seeds per hole at a depth of about 4 cm. Thinning was later done to one plant per hole. The plots were manually weeded at 3<sup>rd</sup> and 7<sup>th</sup> weeks after planting (WAP). The plots received single application of 200 kg/ha compound fertilizer (NPK 15-15-15). Matured heads were harvested starting from 16 weeks after planting (WAP) and the seed yield per ton for each plot was also determined.

Soil temperature was monitored weekly using soil thermometer inserted to 15 cm depth at 1500 h at each measuring dates and soil

**Table 1.** Some meteorological variables at site of experiment during sunflower growth.

Rainfall (mm)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
	1.2	7.4	25.7	45.3	118.6	219.1	272.3	315.8	247.1	168.3	57.5	31.4
Min. Temp (°C)	18.9	20.4	22.5	22.1	21.6	21.1	20.7	21.4	21.8	21.9	21.6	19.8
Max. Temp.(°C)	32.0	32.7	33.4	32.7	31.7	30.9	29.6	29.2	29.5	30.6	31.8	30.9
VPD (KPa)	2.7	3.0	3.5	3.7	3.1	3.3	2.6	2.4	2.7	2.9	3.1	2.6
Total sunshine (h )	190	219	231	198	189	173	116	95	124	194	223	185
Solar radiation (MJ/m <sup>2</sup> /day)	13.2	15.6	17.3	16.8	17.8	16.2	13.5	10.3	13.4	15.3	15.0	13.7
E <sub>o</sub> (mm/month)	204	182	233	141	109	97	90	88	104	115	133	151

E<sub>o</sub> (open water evaporation)  
 Temperature and rainfall (monthly means of daily values or monthly totals)  
 Air temp min, max, mean  
 RH (%; 09.00h)  
 Incoming solar radiation (Rn)

moisture content was measured weekly by gravimetric method using core sample collected at the plots at 0-15 cm depth and oven dried at 105°C for 24 h. Agronomic characters sampled were root and shoot biomass, plant height, 50% flowering date, yield and yield components. Root and shoot biomass were oven-dried at 80 °C for 48 h and dry weights were recorded. Leaves were clipped off the stems and leaf area was measured at 50% flowering date with leaf area meter LiCor 2000 (Mayashi Denko, Japan). Matured heads were harvested starting from 16 weeks after planting (WAP) and the seed yield per ton for each plot was also determined. A range of availability of resources was generated by manipulation of row spacing (plant population density). Large numbers of individuals were taken to assess plant-plant variation in biomass accumulation. The onset of intra-specific competition was inferred from the CV of plant biomass (hierarchies among plants) within same stand and among treatments. This statistical parameter reveals the existence of plants with differing competitive ability within the same stand density (Edmeades and Daynard, 1979). Plant growth rate during the critical period for seed set (PGRc), the proportion of growth partitioned to reproductive organs (P<sub>R</sub>) and the minimum assimilate requirement per seed (λ) were computed. ReGRc - Growth rate during the critical period was calculated as the ratio between accumulated biomass in shoots or reproductive structures and the duration of the period, assuming reproductive biomass is negligible at the beginning of the critical period. Seed set Efficiency (Ef) was computed from the ratio of SNP and ReGRc, the minimum assimilate requirement per seed, (λ: mg/seed/day) was estimated as the inverse of the predicted maximum efficiency in seed set (Vega et al., 2003)

$$\begin{aligned} \text{ReGRc} &= \text{PRc} \cdot \text{PR} \dots\dots\dots 1 \\ \text{Seed set Efficiency (Ef)} &= \text{SNP} / \text{ReGRc} \dots\dots\dots 2 \\ \lambda &= 1 / \text{Ef} \dots\dots\dots 3 \\ \text{P}_{Rc} &= \text{ReGRc} / \text{PRc} \dots\dots\dots 4 \end{aligned}$$

Kipp pyranometers (Kipp and Zonen, Delft, Holland with double glass domes) facing up were used for measurement of incident global radiation and two net pyrradiometers for net all-wave radiation from above and below crop canopies. The radiation sensors were mounted at 3 levels. Probes were installed at on 4m mast to monitor incident global radiation and total net radiation received above the canopy, those mounted 1m below the canopy provided measurements of net radiation transmitted through the canopy. Four tube net radiometers were placed at ground level in each subplot to measure net radiation at the soil surface. The average of the data from these probes at the three levels represents the total global radiation transmitted across the entire field.

Measurements were made once a week during the period of dry matter sampling and between 1000 and 1400 h local time. Radiative flows were recorded automatically with programmed data loggers (21x, Campbell Scientific, Logan, UT) every second every minute. All hourly data represents an average of 60 consecutive readings. Radiation balance is computed as the difference between incident and transmitted radiation (reception at canopy and loss as measured below the canopy/storey), this gives the radiation intercepted by the entire canopy (R<sub>int</sub> = R<sub>inc</sub> - R<sub>trans</sub>). PAR is computed as 0.45 of incoming solar radiation (Kiniry et al. 1998). Using the means for each measurements/subplot, plant dry mass/ground area (m<sup>2</sup>) was plotted as a function of IPAR (MJ/m<sup>2</sup>), the slope of each line was taken as efficiency of radiation utilization (RUE) in g/MJ of PAR. (Kiniry et al., 1998). Sensors were placed above (2.5 m from soil surface) and within the canopy (0-2 m). The fraction of intercepted photosynthetically active radiation (fIPAR) was calculated as

$$\text{FIPAR} = \frac{\text{Irradiance at the sensor}}{\text{Irradiance above the canopy}} \dots\dots\dots 5$$

These calculation require the determination of the irradiance at the sky light above the canopy, the sun elevation and azimuth for a selected time interval and PAR was considered as 45% of global radiation. The fIPAR of different canopy layers were related to the corresponding LAI values and an exponential function (fIPAR = 1 - e<sup>-kLAI</sup>) was fitted (after Maddonni et al., 2001). Extinction coefficient (K) was derived from this exponential function. Some meteorological variables at the site of the experiment is presented in Table 1. Data collected from the field were subjected to analysis of variance (ANOVA) to determine the effects of treatments on the parameter measured. The treatment means were separated using least significant difference (LSD) test at 5% level of probability.

## RESULTS AND DISCUSSION

### Soil hydrothermal status

Although, differences were obtained in the values of soil temperature (taken at 5 cm depth at 1500 h) during the course of sunflower growth, treatment effects were significant (Figure. 1) . High density of plant stand under narrow row spacing (60 x 30 cm) reduced soil temperature at 5cm depth. The values of soil moisture content at 10 cm depth (Figure 2) were similar in the early stage of the

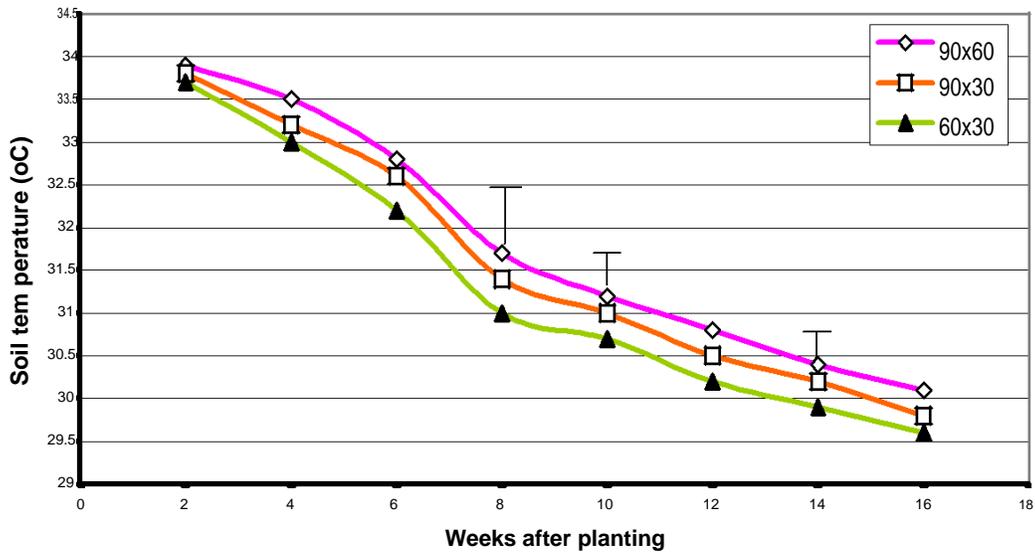


Figure 1. Effect of row spacing on soil temperature in sunflower cultivars.

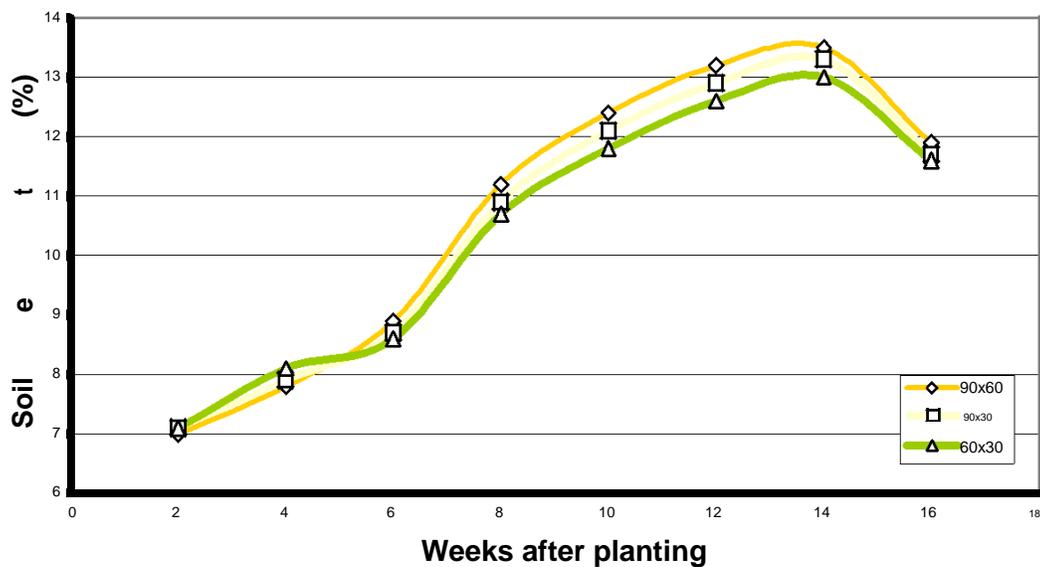


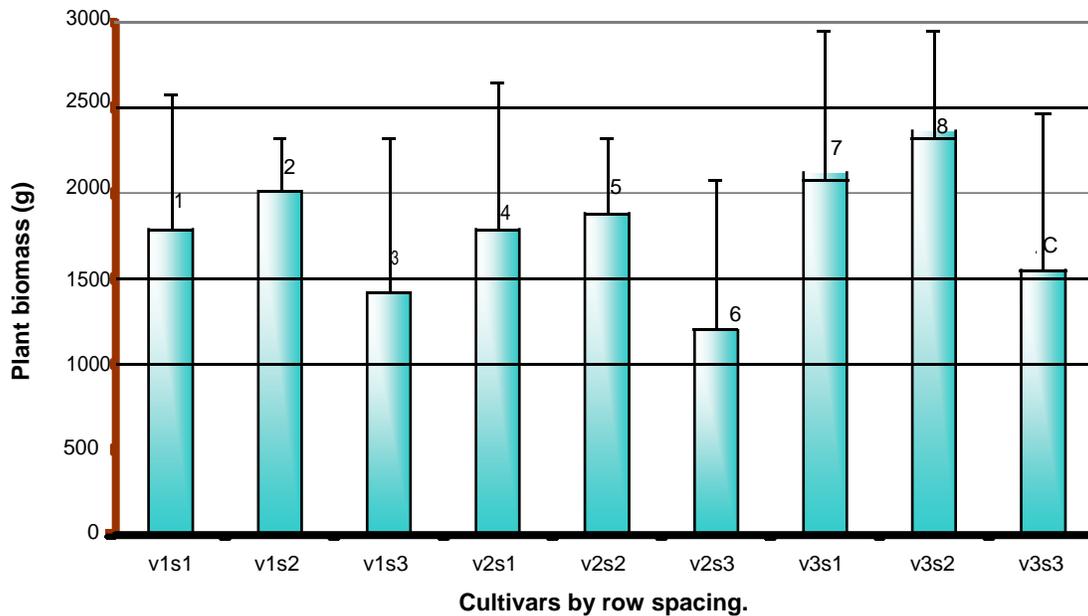
Figure 2. Effect of row spacing on soil moisture content in sunflower cultivars.

development of sunflower but differences in the values of soil moisture content were attained at 8 weeks after planting (WAP). Sunflower grown under wide row spacing had higher soil moisture contents, and this trend was consistent in the three varieties. Under dry land conditions, sunflower is reported to have extracted water from deeper soil profile, this trait enabled the crop to tolerate prolonged dry periods (Unger et al., 1976; Connor and Jones, 1985; Meinke et al., 1993). Soil water availability is a major factor affecting crop productivity in the different cropping systems in many parts of the world and the correct estimation of soil water supply is important to the

efficiency of yield prediction in crop models (Monteith, 1989).

### Biomass accumulation

For all plant densities (averaged across row spacing), cultivars differed in shoot biomass accumulation (Figure 3), these differences may be responsible for the established hierarchies among plant stands. The phenomenon of hierarchical growth among plants within a stand is related to the intensity of intra-specific competition in response to crowding (Vega et al., 2001). Among the sunflower cultivars



**Figure 3.** Plant-plant variations in biomass in sunflower cultivars as affected by row spacing. 1(Funtua 90x30 cm), 2 (Futual 90x60 cm), 3 (Futua 60x30 cm): 4 (Record 90x30 cm), 5 (Record 90x60 cm), 6 (Record 60x30 cm): 7 (Isaaka 90x30 cm), 8 (Isaaka 90x60 cm), 9 (Isaaka 60x30 cm): Bars represent intra-plant coefficient of variation (cv).

ars, differences in row spacing enhanced plant-plant variation in terms of accumulated biomass. This phenomenon which affected grain yield and the stability of dry matter partitioning to seeds. Size dependent reproductive efforts reflected in differences in ability to partition accumulated biomass to seeds, seed number and seed yield per plant. Hierarchical growth among plants within a stand could therefore explain the observed size dependent reproductive efforts in sunflower in this study. Large plants in wide row spacing have competitive advantage and could be identified with high capacity for resource capture and use for seed production (Maddonni et al., 2003). Differences in sunflower cultivar's responses to row spacing manifested in differential ability to transform accumulated biomass to seed production under different intensities of inter plant competition. Kernel number at harvest is reported to be a function of the physiological condition of the crop at a critical period bracketing anthesis (critical period for seed number determination) (Egli, 1998; Ball et al., 2000; Vega et al., 2001). This growth phase seemed to be the stage when kernel number is most susceptible to stress (possibly inter plant competition). Gradner and Gardner (1983) suggested that unfavorable environmental conditions just prior to and during anthesis can cause cessation of head development and seed/kernel abortion while Pressman et al. (2002) attributed seed abortion to shortage of assimilate supply to developing seeds. Sunflower cultivar's responses to row spacing appeared to be related to differences in cultivar's ability to transform biomass produced during post-flowering period into kernel weight. The pattern of source-sink

ratio during effective grain filling period might explain kernel weight responses and the modifications in KNP. Borrás and Otegui (2001) attributed effect of stand density on final seed yield and this may be due to the occurrence of competition for assimilates during grain filling period. Therefore, the physiological state of a plant at the beginning of the critical period could condition reproductive fate (Egli, 1998; Ball et al., 2000; Vega et al., 2001).

### Reproductive growth, biomass partitioning and seed set efficiency

Seed yield/ha increased as plant density increased although yield of the individual plants and their components were significantly reduced suggesting a compensation of higher plant densities on seed yield in sunflower (Table 2). Differences in seed yield and seed number/plant among the genotypes suggest a cultivar-specific potential seed number (reproductive sinks per plant) in sunflower. The magnitude of yield per land area in narrow rows could be due to increased grain number. Other yield components important to the seed yield attained were reduced grain mass/plant, number of seeds/head and reduced head diameter. The components of yield which improved in wide row crop are head diameter, number of seeds/head and 100 seed weight and seed yield per plant. Late season sunflower rarely attained full canopy cover possibly due to non-conductive growing environments of the late season characterized by concurrent str-

ess situation (soil water deficits, and high temperatures/vpd). Although, sunflower is reported as a hardy crop characterized by high drought tolerance (Connor and Jones, 1985; Rachidi et al., 1995), the concurrent stress factors of the late season could have affected dry matter accumulation and seed set efficiency. Among the row spacing treatments, differences were obtained in shoot biomass (Sp) and plant growth rate at the onset of active head growth (ReGRc), these differences could explain variations in KNP. Significant relations between KNP and plant biomass at start of active head growth is reported (Vega et al., 2001). Narrow row crops whose growth have been reduced early along the cycle possibly due to high intra-specific competition had decreased biomass partitioning to reproductive structures during the critical period and are more prone to barrenness in addition to increasing kernel set variability (Table 3). The effects of Sp and ReGRc on final KNP seemed to be exerted through current assimilate partitioning during the critical period. Reproductive characters such as reproductive partitioning ( $P_R$ ) and seed set efficiency in terms of seed number per unit of reproductive growth (Ef) (which comprised about 50% of shoot growth) improved under wide row spacing. Seed set efficiency (Ef) differs among cultivars, and may be due to the higher minimum combined demand for assimilate resulting from a higher  $\lambda$  and number of simultaneously developing sinks as was obtained for the cultivar Record with high branching pattern. However, EF increased in wide row spacing which was characterized by low reproductive growth.

### Radiation interception and use

Radiation conversion coefficient, the absorption of radiation in relation to dry matter accumulation ( $E; g\ dm.MJ^{-1}$ ) differed among the cultivars (Table 3). Trends in the values of absorbed radiation in relation to seed production (RUE) were within those reported elsewhere for sunflower (Vega et al., 2003; Agele, 2003). However, the range of values of RUE obtained in our study may be attributed to late season high vpd (c.2.7 kPa), high vpd is reported to enhance RUE in crops (Takami et al., 2002). Similar RUE was attained by the three densities treatments despite the high radiation interception by high density plants. It appears that the change in yield in response to row spacing was a linear function of change in fractional PAR interception. Yield increased for wide rows spacing can be due to increases in fractional PAR interception. Despite the high levels of incident radiation in the late season period, close spacing depressed radiation conversion coefficients in sunflower. High temperatures enhanced leaf photosynthetic saturation (Gilett et al., 2001), the regimes of soil and air temperatures in the late season might be sufficient to manifest significant effects on radiation conversion coefficient (E). In general, radiation interception was high despite of the low LAI and biomass production of the late season crop (Table 3).

This trend may be attributed to high extinction coefficient (k) and high radiation use efficiency of sunflower (Chapmann et al., 1993; Ball et al., 2000; Vega et al., 2001). Sunflower grown under wide row spacing intercepted less radiation than their counter-parts in narrow rows. Although leaf area/plant was greatest in wide row crops the sparse density resulted in low radiation interception compared to high density of plant stand. In wide row crops, low intra-specific competition ensures a more uniform growth of individual plants within a stand; this attribute did not result into improved light attenuation/perception especially. It can be inferred that light attenuation coefficient (k) improved under high density sunflower. Leaf re-orientation and hence the plasticity of plant canopies offset the effects of spatial arrangement and caused plant to react to fill empty spaces especially under wide row cropping. This behaviour of the canopy is reported to affect light interception (Maddonni et al., 1999). The plasticity of plant canopy based on leaf re-orientation is possibly a mechanism underlying the biological processes responsible for the maintenance of daily light interception nearly independent of inter-row distance (Maddonni and Otegui, 2004).

### Interaction effects

The main factors had independent (constant) effects for many growth and yield characters measured which is an indication that the two sets of treatment were independent in their effects on sunflower. However, pronounced dependence of expression of some cultivar's attributes on plant spacing was observed for sunflower particularly for many growth and yield characters measured in this study (Table 2 and 3). Based on these analyses, significant interactions between plant spacing and variety for many growth and yield characters and spacing are the predominant source of variation. These interactions were also remarkable on dry matter accumulation, leaf area development, reproductive partitioning, and the efficiency of seed set and radiation use.

### Conclusion

Contrasting responses to crowding was obtained in sunflower varieties cropped at different row spacing. Among the varieties, these responses appeared to be related to establishment of hierarchies among plants and variations in the efficiencies of seed set.

In wide row crops, low inter plant competition and high assimilate production at the critical period for kernel number determination appeared to have enhanced biomass allocation to reproductive structures and reduced plant barrenness (Table 4). Hence in wide row crops, there could be a more balanced allometric relationship between the head and the seeds (stability in biomass partitioning from vegetative to reproductive structures). The effect of row spacing on yield components (KNP and seed yield)

**Table 2.** Growth and yield characters of sunflower as affected by cultivar type and row spacing.

Treatments	Days to 50% flowering (Days)	Total Dry Matter (g)	Stem girth (cm)	Leaf area (cm <sup>2</sup> )	Height at flowering (cm)	Head Diameter (cm)	100 seed weight (g)	Seed Yield (t/ha)
V <sub>1</sub> S <sub>1</sub>	73	240.33	9.0	395.27	255	14.63	6.39	1.81
V <sub>1</sub> S <sub>2</sub>	73	254.33	12.0	437.70	250	15.73	7.56	1.26
V <sub>1</sub> S <sub>3</sub>	71	124.67	4.0	259.00	240	12.67	5.71	1.48
V <sub>2</sub> S <sub>1</sub>	68	240.67	8.0	337.27	235	13.67	6.03	1.67
V <sub>2</sub> S <sub>2</sub>	66	249.67	12.0	450.43	192	15.60	6.97	1.18
V <sub>2</sub> S <sub>3</sub>	66	125.67	3.0	219.90	235	12.40	5.29	1.54
V <sub>3</sub> S <sub>1</sub>	62	272.00	½.0	363.53	195	15.07	6.74	1.88
V <sub>3</sub> S <sub>2</sub>	61	280.67	16.0	563.50	185	16.53	7.83	1.29
V <sub>3</sub> S <sub>3</sub>	62	125.67	0.77	320.37	180	13.27	5.85	2.13
LSD Variety	1.05	4.63	0.14	11.43	0.19	0.35	0.27	0.11
Spacing	NS	6.08	0.19	14.24	0.24	0.54	0.32	0.21
Interactions	NS	19.54	NS	24.67	0.42	NS	NS	NS

**Table 3.** Plant-plant variability, reproductive partitioning and seed set efficiency of sunflower as affected by cultivar type and row spacing.

	<sup>1</sup> PGRc (g.m <sup>-2</sup> day <sup>-1</sup> )	<sup>2</sup> ReGRc (g.m <sup>-2</sup> day <sup>-1</sup> )	<sup>3</sup> P <sub>R</sub>	<sup>4</sup> EF	<sup>5</sup> λ	No. of Seeds /plant	<sup>6</sup> Yp (g/plant)	τK	<sup>8</sup> RUE shoot (MJ. m <sup>-2</sup> day <sup>-1</sup> )	seed
V1S1	4.94	11.73	2.35	64.67	0.0155	758.3	34.8	0.37	0.38	0.94
V1S2	4.21	12.55	2.98	64.44	0.0153	808.7	50.4	0.27	0.47	1.04
V1S3	4.45	11.21	2.52	56.36	0.0172	631.5	26.5	0.24	0.33	0.87
V2S1	4.90	11.64	2.36	59.86	0.0167	697.2	33.2	0.29	0.61	2.03
V2S2	4.22	12.49	2.96	66.07	0.0152	824.9	48.4	0.22	0.68	2.11
V2S3	4.51	11.11	2.47	51.43	0.0196	586.7	21.4	0.23	0.53	1.92
V3S1	4.93	11.76	2.38	76.15	0.0141	836.4	36.2	0.22	0.67	1.45
V3S2	4.24	12.44	2.95	74.32	0.0135	924.2	51.5	0.16	0.71	1.72
V3S3	4.21	11.07	2.64	59.59	0.0168	659.7	39.5	0.17	0.62	1.36
<b>LSD (0.05)</b>										
Variety	0.84	0.76	0.41	7.82	0.0017	51.3	6.5	0.54	0.81	0.77
Spacing	0.67	0.53	0.36	5.92	0.0012	44.7	5.8	0.39	0.72	0.71
Interactions	NS	0.81	0.52	8.46	NS	63.6	NS	NS	NS	0.86

1 (Growth rate), 2 (Plant growth rate during the critical period for seed set), 3 (proportion of growth partitioned to reproductive organs), 4 (seed set efficiency), 5 (minimum assimilate requirement per seed), 6 (seed yield/plant), 7 (extinction coefficient) , 8 (radiation use efficiency for biomass and seed production)

**Table 4.** Important relationships of reproductive phases and seed yield of soybean and some weather variables of the growing season

Parameters	Regression equations	r <sup>2</sup>
<b>EF and plant biomass (SP)</b>		
90 x 30 cm	y = 22.54x + 27.8	0.95
90 x 60 cm	y = 12.9x + 43.1	0.82
60 x 30 cm	y = 8.8x + 40.6	0.74
<b>IPAR and plant biomass (SP)</b>		
90 x 30 cm	y = 0.0372x + 0.63	0.95
90 x 60 cm	y = 0.0483x + 0.7932	0.91
60 x 30 cm	y = 0.0983x + 0.3246	0.96
<b>fIPAR and thermal time (TT)</b>		
90 x 30 cm	y = 0.0001x + 0.14	0.89
90 x 60 cm	y = 0.0001x + 0.082	0.93
60 x 30 cm	y = 0.0001x + 0.26	0.95
<b>fIPAR and Seed yield (Yp)</b>		
90 x 30 cm	y = 0.004x <sup>2</sup> - 0.05x - 0.07	0.99
90 x 60 cm	y = 0.004x <sup>2</sup> - 0.124x - 0.025	0.96
60 x 30 cm	y = 0.006x <sup>2</sup> - 0.05x - 0.06	0.99

seems to be exerted through current assimilate partitioning during the critical period. In narrow row crops, low RePGRc at the onset of active head growth resulted in the impairment of biomass allocation to reproductive structures. Drastic reduction in KNP under low RePGRc was accompanied by reduction in apical head biomass. Row spacing is cultural practices that may modify resource availability per plant, a practice which may influence the ability of each plant to allocate to the ear/head minimum assimilate required for seed set. Increased stand densities and hence inter-plant competition, reduced ability for resource capture as evident in biomass production and impaired grain production at high densities.

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