Hindawi Publishing Corporation
International Journal of Agronomy
Volume 2012, Article ID 980284, 17 pages
doi:10.1155/2012/980284

Research Article

Corn and Soybeans in a Strip Intercropping System: Crop Growth Rates, Radiation Interception, and Grain Yield Components

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Received 17 June 2011; Accepted 16 January 2012

Academic Editor: David Clay

Crop growth rates (CGR), radiation interception (IPAR), yields, and their components were determined in two crops monocultures (using one corn and two soybean genotypes) and in intercropped "strips," during three growing seasons. Corn yield in the strips significantly increased in the three seasons (13–16%) as compared to that in the monocultures. This response was due to increased yield in corn plants of the border rows of the strips, which was highly correlated to an increased IPAR, allowing high CGR at critical crop stages. As a result, more dry matter was partitioned to grain and also an increased number of ears per plant were generated. Conversely, yields of soybeans in the strips were 2 to 11% lower than that in the monocultures, with variable significance depending on soybean cultivar and/or year. Grain number per unit area was the yield component most closely associated to yield variation in both crops. We believe that if yield components of this system are more closely identified, more appropriate genotypes will fit into strip intercropping, thus contributing to the spread of this technique and thus to the sustainability of actual massive monocultured agricultural systems.

1. Introduction

A crop association essentially consists of growing two or more crops in the same area of land at the same time. Supported by the conventional accepted niche theory [1], the aim of this crop system is to optimize factors and environmental resources usage [2], thus leading to an increased yield output of the mixture. In strip intercropping, the width of the strip needs to be wide enough to allow seeding and harvesting operations although narrow enough to allow the interaction of the components of the mixture to occur [3]. Depending on the scenario and the circumstances, interaction is not only dependent on the availability of resources but also on the structure of the crops and cultivars used.

Corn grain yield is the result of the grain weight (GW) multiplied by the grain number per unit area (GNUA) [4]. GNUA also depends on the crop physiological condition during the critical period [5]. As crop growth rate (CGR) and also plant growth rate (PGR) increases, the number of grain fixed within the flowering period also increases [6]. Hence, this relationship is a good indicator of the crop ability for grain fixation, under variable environmental (water, nitrogen, and radiation) conditions [7]. The above-described relationship, also influenced by the genotype, is highly related to two factors: (i) irradiance availability and (ii) crop architecture.

Yield is also defined as the product of GW by GNUA in soybeans. Contrary to corn, subcomponents of GNUA are defined within a very wide range of time of the crop cycle, from crop emergence (VE) to the latest differentiated pods (R2). Adverse environmental conditions in the earlier stages of the crop may be compensated, if the quality of the environment improves later on, providing the final grain number is not affected [8]. Thus, the critical period in soybeans is not as precise as it is in corn, since it is related to the grain filling period and also to partial compensations in GW. Temperature and radiation during the critical period are key factors controlling the crop growth rate (CGR) and

the grain number per unit area (GNUA) under nonrestricted soil conditions.

In the nonirrigated, extensive summer crop production systems of Argentina, radiation is the key factor in determining yields, providing no nutrients and rainfall shortage occur. Since the intercepted radiation (IPAR) and its efficiency (Radiation Use Efficiency (RUE)) are central factors in defining the plant yield outputs, we studied the growth and the variations in yields and its components in both crops (one corn, two soybeans genotypes) under monocultures and in strips intercropping systems, since we believe that our findings may contribute to the selection of traits more suitable for genotypes, thus contributing to local knowledge generation, the basis for the adoption of this system.

2. Material and Methods

2.1. Experimental Conditions. Experiments were conducted in Monte Buey, Argentina (32°94′41″ S 62°58′97″ W), during 2006-2007, 2007-2008, and 2008-2009 (C1, C2, and C3, resp.), in a highly productive typic Argiudol soil [9], cultivated under direct drilling technique since 1996.

The experimental units consisted in 36 rows, 8 m length × 19 m width plots, with an interrow spacing of 0.52 m. Treatments included the following crops monocultures: corn (intermediate cycle single DK 684 hybrid, 665–685 degree-days since emergence to female flowering, 119 Julian days to relative maturity) and two soybean genotypes: MG III, cv DM 3700RR (126/145 Julian days to R8), and MG V, cv DM 4800RR (134/155 Julian days to R8) and also "strips" of both crops: in corn strips corn was planted in the 12 central rows, with 12 rows of soybeans on each side; in the soybean strips, soybeans were planted in the 12 central rows with 12 rows of corn on each side. Thus, a total of seven treatments were tested: three monocultures (one corn, two soybeans), two corn strips bordered by soybeans (MG III or V), and two soybean strips (MG III or V) bordered by corn.

In all treatments, corn was planted on October the 12th (C1, C2) and October the 14th (C3). Corn stand density was 8.2 seeds m^{-2}. In all treatments, soybeans were planted either in the monocultures or in the strips on November 10th (C1), November 16th (C2), and November 9th (C3). Soybean stand density was 24 seeds m^{-2}. All plots were planted with the rows oriented east-west.

Treatments were placed under a complete randomized block design with four replications. Nitrogen (UAN-N-P-K. 32-0-0, 200 Kg N ha^{-1}) and phosphorus (Mono-ammonium phosphate) 12-52-0, 24 Kg N ha^{-1}, and 104 Kg P ha^{-1}), plus SO_4Ca, 350 Kg ha^{-1} were, respectively, band and broadcast applied every year. Insect and weed management were carried out following recommended standards in the area to allow maximum crop yield potential. Temperature, radiation, and rainfall data were recorded with an automatic weather station located at 1500 m from the experiment site.

2.2. Irradiance. Radiation interception was measured soon after crop emergence and every 20 days until physiological maturity. A 1 m, Line Quantum Sensor (LI-191SA, LI-COR, Lincoln, NE) was used. The sensor was placed in the interrow (to capture PAR transmitted to the soil) and also placed above the crop canopy (to measure the total PAR received by the crop). In the strip treatments, additional measurements were made at different crop heights not only in the border row but also in the central row of each plot. Intercepted PAR (IPAR) by the crop was calculated according to Gallo [10]:

$$\mathrm{IPAR} = I_o - \mathrm{Rt}, \tag{1}$$

where IPAR is the PAR intercepted by the crop, I_o is the total radiation above the crop canopy, and Rt is the radiation at soil level. IPAR during crop cycle was calculated as the area under the curve.

RUE was calculated as the slope of the total biomass regressed to the IPAR captured through the complete crop cycle in both crops [11] and calculated as dry matter (g) per unit of intercepted PAR radiation (Mj^{-1}), in C1, C2, and C3.

2.3. Crop Growth Rate. CGR was determined at six sample dates from crop emergence to physiological maturity, by using plant dry weight of the strip and also of the monocultures. In strips, plants of rows 1, 3, 5, 7, 9, and 11 were used. All plants were dried at 65°C in an air circulating oven, during 72 hours. The following formula was used to calculate the growth rate [12]:

$$\mathrm{CGR} = \frac{W_2 - W_1}{t_2 - t_1}, \tag{2}$$

where CGR is the crop growth rate (g m^{-2} d^{-1}), W is aboveground plant biomass (g) at t_1 and t_2 days after crop sowing.

2.4. Yield. Plants randomly selected within the central four rows in the monoculture plots and those remaining of previous harvests in the strip plots, located within the central 3 m of every single row, were cut and then threshed in an experimental grain thresher. In soybeans, total pods number was registered and also grain weight determined. Crop yields in the strips were then calculated as the average yield of 12 rows and compared with yields obtained in the monocultures. All grain weights were corrected to the standard 13.5% grain humidity and reported as kg ha^{-1}.

2.5. Yield Components: Corn. Ears per plant were calculated by dividing the total number of ears per plant by plant density. Grain dry weight (GW) was estimated by using the weight of 500 grains, grain number per unit area (GNUA) was calculated as a yield divided by GW, and ear number per unit area (ENUA) was calculated by multiplying plant density with ears per plant (ENP). The grain number per ear was calculated as follows:

$$\mathrm{GNE} = \frac{\mathrm{GNUA}}{\mathrm{PN} * \mathrm{ENP}}, \tag{3}$$

where GNE is the number of grains per ear, GNUA is the number of grains per unit area, PN is the number of plants per unit area, and ENP the number of ears per plant. The number of grains per plant (GNP) was calculated by multiplying ENP by GNE.

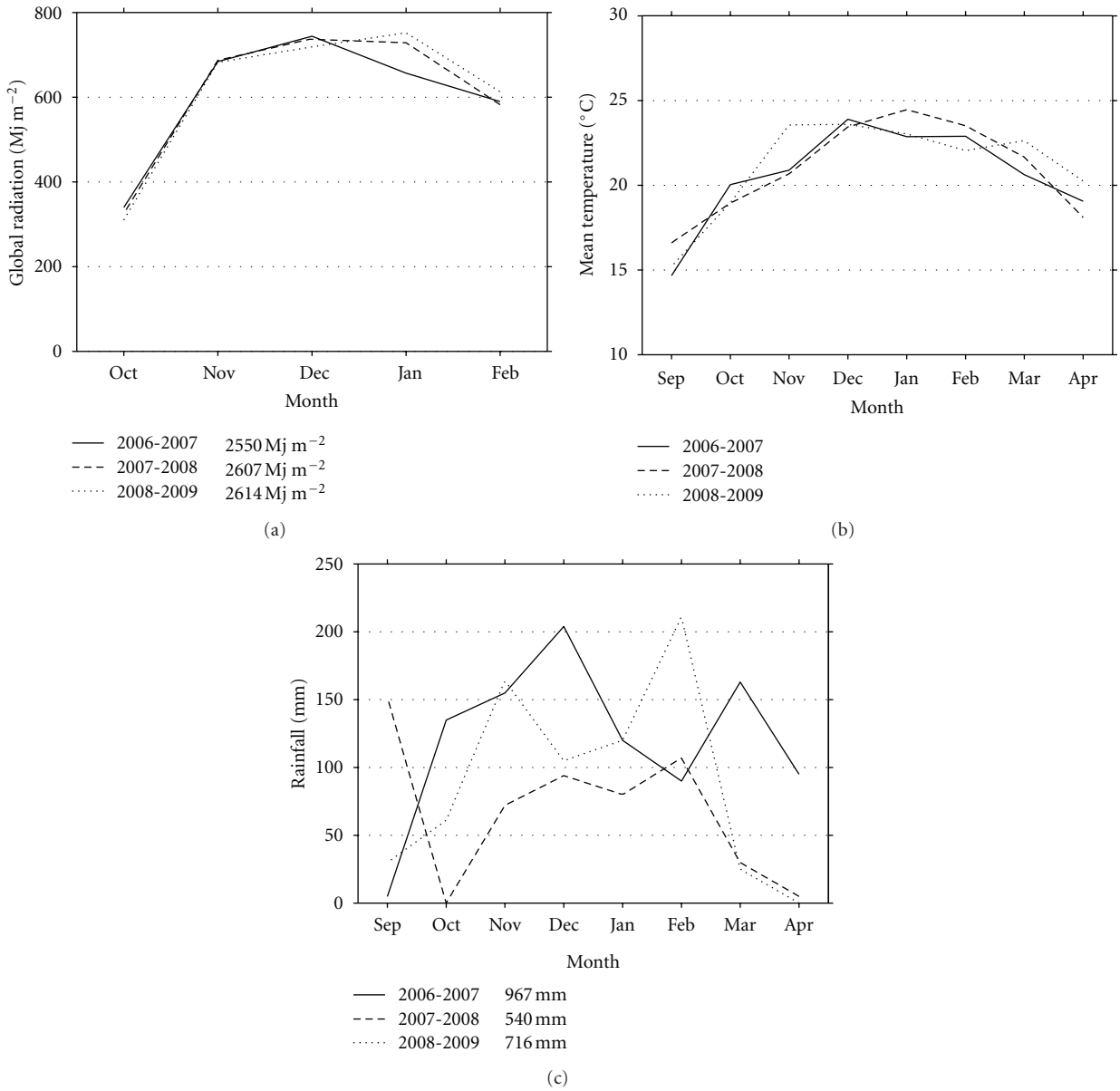

Figure 1: Weather conditions: PAR (a), mean air temperature (b), and rainfall (c) during crop cycles in C1, C2, and C3.

2.6. Yield Components: Soybeans. Pod number per plant (PNP) was calculated as the average number of pods of 10 plants randomly selected in every harvested row. The number of pods per unit area (PUA) was calculated by multiplying PNP by plant density (PD) at harvest time. Grain dry weight was estimated by weighing 500 grains. The number of grains per unit area (GNUA) was determined by dividing grain yield by grain dry weight (GDW). The number of grains per pod (GPP) was determined by dividing GNUA by pod number.

2.7. Statistical Analysis. Experimental design consisted in seven treatments under a complete randomized block design with four replicates. Variables were evaluated by multivariate ANOVA. For those variables sequentially measured along the crop cycle (e.g., plant dry weight, leaf area index), a second-order interaction between treatments and year at each harvest time was calculated. Mean separations were made using Least Significant Difference (LSD) test. All comparisons were set at $P < 0.05$. The statistical package Statgraphics Plus (v.5.1) was used. Variables or indices showing curvilinear responses were analyzed using Graph Pad Prism (Golden Software Inc.) statistic software package.

3. Results and Discussion

Global radiation and air temperature showed a similar pattern during C1, C2, and C3 (Figures 1(a) and 1(b)): a steady-increase pattern was clearly evident from mid-September to early January and a slight decrease (as crops

Table 1: PAR interception (IPAR) (Mj m^{-2}). Locations 1, 7, or 12, corresponds to the northern, central, and southern rows, respectively. In monoculture, measurements were made in the center of the plot. Means in a column followed by same letter are not significantly different ($P < 0.05$).

	Location (rows)	Total IPAR(Mj m^{-2})	IPAR around silking (Mj m^{-2})	IPAR after silking-R6 (Mj m^{-2})
Strip Corn + soybean MG III	1	1275.8a	408.4a	654.6a
	7	1000.7b	320.1b	515.5b
	12	1101.4a	386.9a	615.6a
Strip Corn + soybean MG V	1	1277.2a	408.9a	655.7a
	7	1001.6b	320.4b	515.8b
	12	1156.9a	387.1a	616.4a
Corn monoculture	Center	1010.3b	323.9b	521.2b
Strip soybean MG III + Corn	1	868.6c	—	379.9c
	7	1190.1d	—	466.3d
	12	1165.5d	—	459.0d
Soybean MG III monoculture	Center	1229.7d	—	477.0d
Strip soybean MG V + corn	1	896.9c	—	394.5c
	7	1227.6d	—	484.2d
	12	1202.2d	—	476.7d
Soybean MG V monoculture	Center	1268.3d	—	495.4d

started accumulating biomass in reproductive tissues) from mid-January to March-April. Global radiation accumulated 2590 MJ m^{-2} in the whole season.

Total rainfall and rainfall frequency patterns were clearly different in each year, with C2 (with a total rainfall of 540 mm) being the driest year as compared to the wetter C1 (967 mm) and C3 (716 mm) (Figure 1(c)).

3.1. Irradiance. In the strip, IPAR was significantly higher in the border rows than in the center rows and also higher than in the monoculture. These significant differences occured around 700 DD (reproductive stage initiation) and more consistently in north row (row 1) than in the south row (row 12), in both corn-soybeans (MG III and V) strips during the three seasons. IPAR was lower in the north rows (row 1) of soybean strips due to the shadow produced by adjacent corn plants (Table 1).

4. Corn

4.1. IPAR and CGR. The relationships between CGR around flowering and IPAR in corn strips with soybeans MG III are shown in Figures 2(a), 2(c), and 2(e) and in corn strips with MG V and in Figures 2(b), 2(d), and 2(f). GCR of the plants located in border rows was higher ($P < 0.05$) as compared to that of plants growing in the inner rows or in the monoculture. This enhanced CGR in corn plants of outer rows was measured in both corn-soybeans associations during C1, C2, and C3.

Since growing conditions around flowering are of major importance in determining crop yield, the greater IPAR may explain the increased values of CGR. Following the same reasoning, Kantolic and Satorre [13] found that 58% of CGR was explained by differences in the IPAR at R1 crop stage.

Table 2: RUE (g Mj^{-1}) in monocultures and intercropped, during C1, C2 and C3.

Treatments	Location (rows)	RUE (g Mj^{-1})		
		C1	C2	C3
Strip corn Soybean III	Row 1	3,25 (a)	3,80 (a)	3,83 (a)
	Row 7	3,16 (a)	3,73 (a)	4,14 (a)
Strip corn Soybean V	Row 1	3,48 (a)	3,80 (a)	3,95 (a)
	Row 7	3,00 (a)	3,72 (a)	4,27 (a)
Corn monoculture	Center	3,19 (a)	3,22 (a)	4,04 (a)
Strip soybean III Corn	Row 1	0,94 (b)	0,58 (b)	0,79 (b)
	Row 7	1,64 (b)	0,52 (b)	1,12 (b)
Soybean III monoculture	Center	0,98 (b)	0,47 (b)	1,00 (b)
Strip soybean V Corn	Row 1	1,21 (b)	0,55 (b)	0,94 (b)
	Row 7	1,23 (b)	0,50 (b)	0,92 (b)
Soybean V monoculture	Center	1,18 (b)	0,46 (b)	0,94 (b)

In our experiments, CGR reached 60 g DW m^{-2} d^{-1} when IPAR values ranged from 14 to 16 Mj m^{-2} d^{-1} in row 1. This figure is similar to those reported by Lindquist et al. [11] and Tollenaar and Migus [14], but higher than those found by Andrade et al. [6] which was also done in Argentina, although in monocultures and at a lower latitude. Increased IPAR levels in row 1 are closely associated to a higher CGR, which seems to be the consequence of higher PAR capture by nonshaded leaves.

4.2. Radiation Use Efficiency (RUE). RUE in the strips did not differ to that in the monocultures ($P < 0.05$) (Table 2).

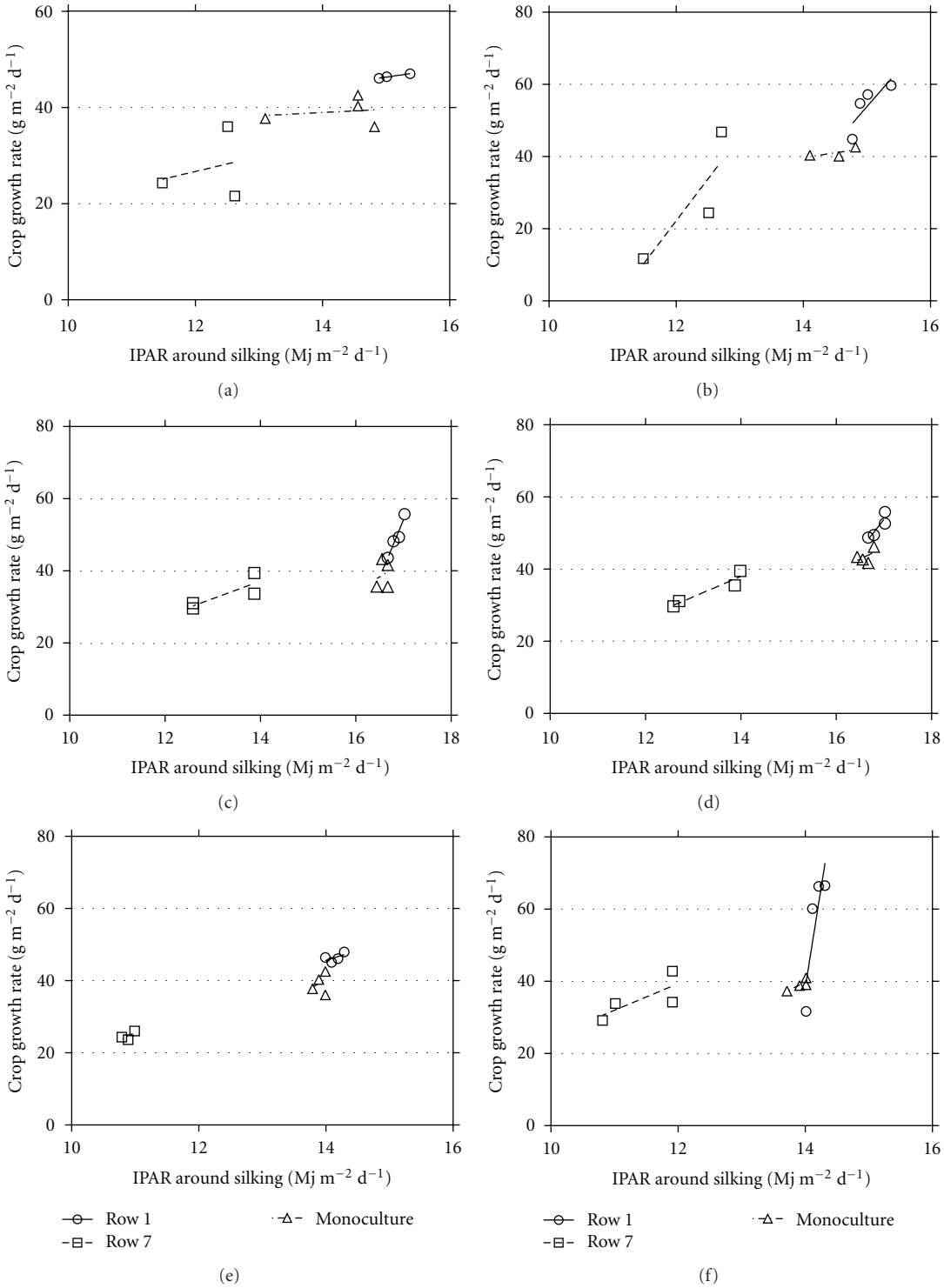

Figure 2: Corn growth rate around flowering related to IPAR in monocultures and in rows 1 (border) and 7 (center) in corn-soybeans MG III, during C1 (a), C2 (c), and C3 (e) and in corn-soybeans MG V, during C1 (b), C2 (d), and C3 (f).

However, total biomass versus IPAR during C1 (Figures 3(a) and 3(b)) was significantly lower than during C2 (Figures 3(c) and 3(d)) and C3 (Figures 3(e) and 3(f)).

High RUE is crucial to maximizing crop efficiency. In corn, RUE values ranged from 3 to 4 g MJ^{-1}. Although plants in row 1 accumulated higher biomass and yielded better, (Tables 1 and 2), RUE did not increase.

4.3. Grain Yield. Yields of corn plants located in the border rows of the corn strips (1 and 12) were higher than that

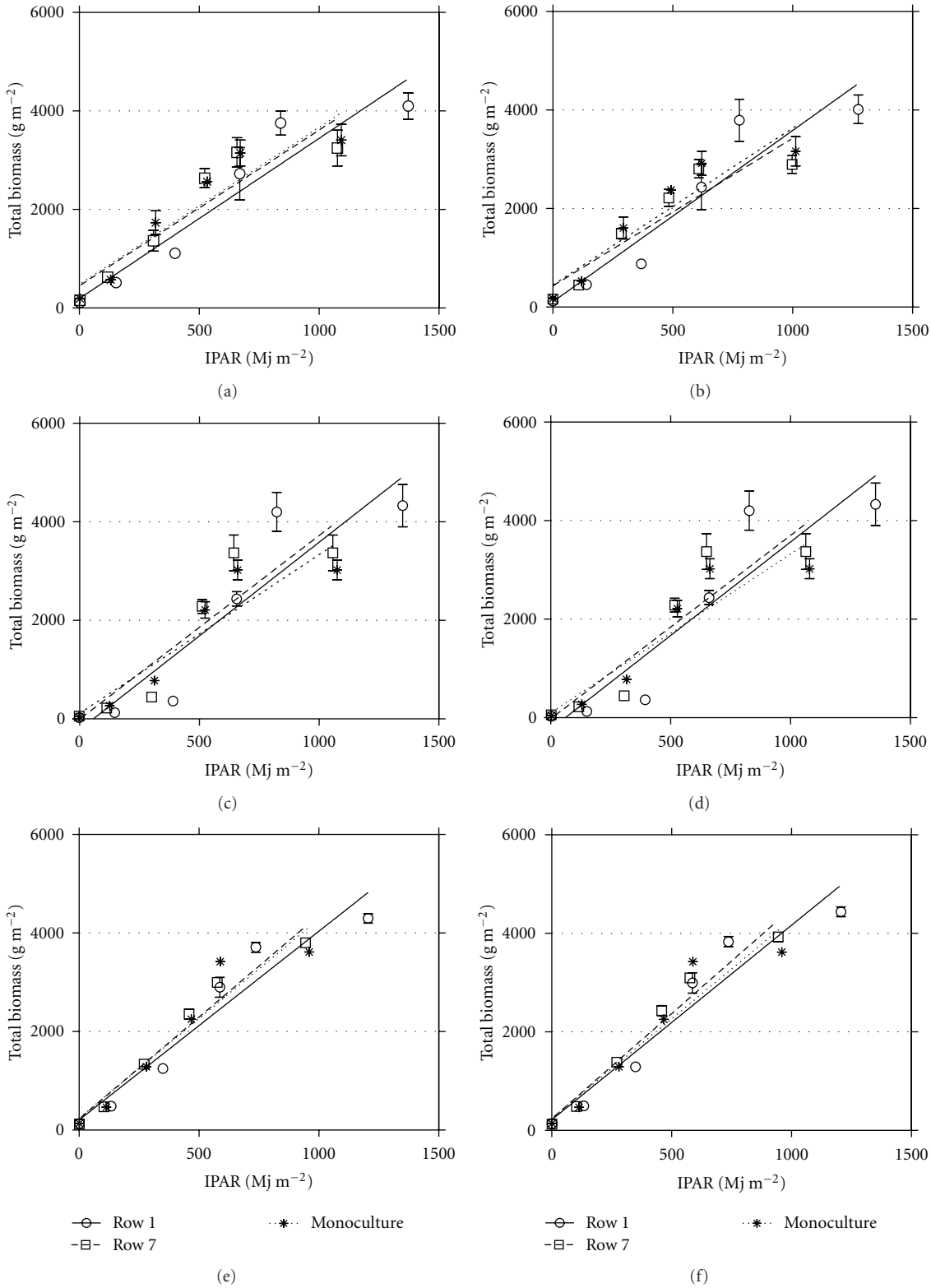

Figure 3: Total biomass versus IPAR in rows 1 (border) and 7 (center) in the strips and in monoculture, during C1 (a, b), C2 (c, d), and C3 (e, f). (a), (c), and (e) correspond to corn-soybeans MG III, and (b), (d), and (f) to corn-soybeans MG V.

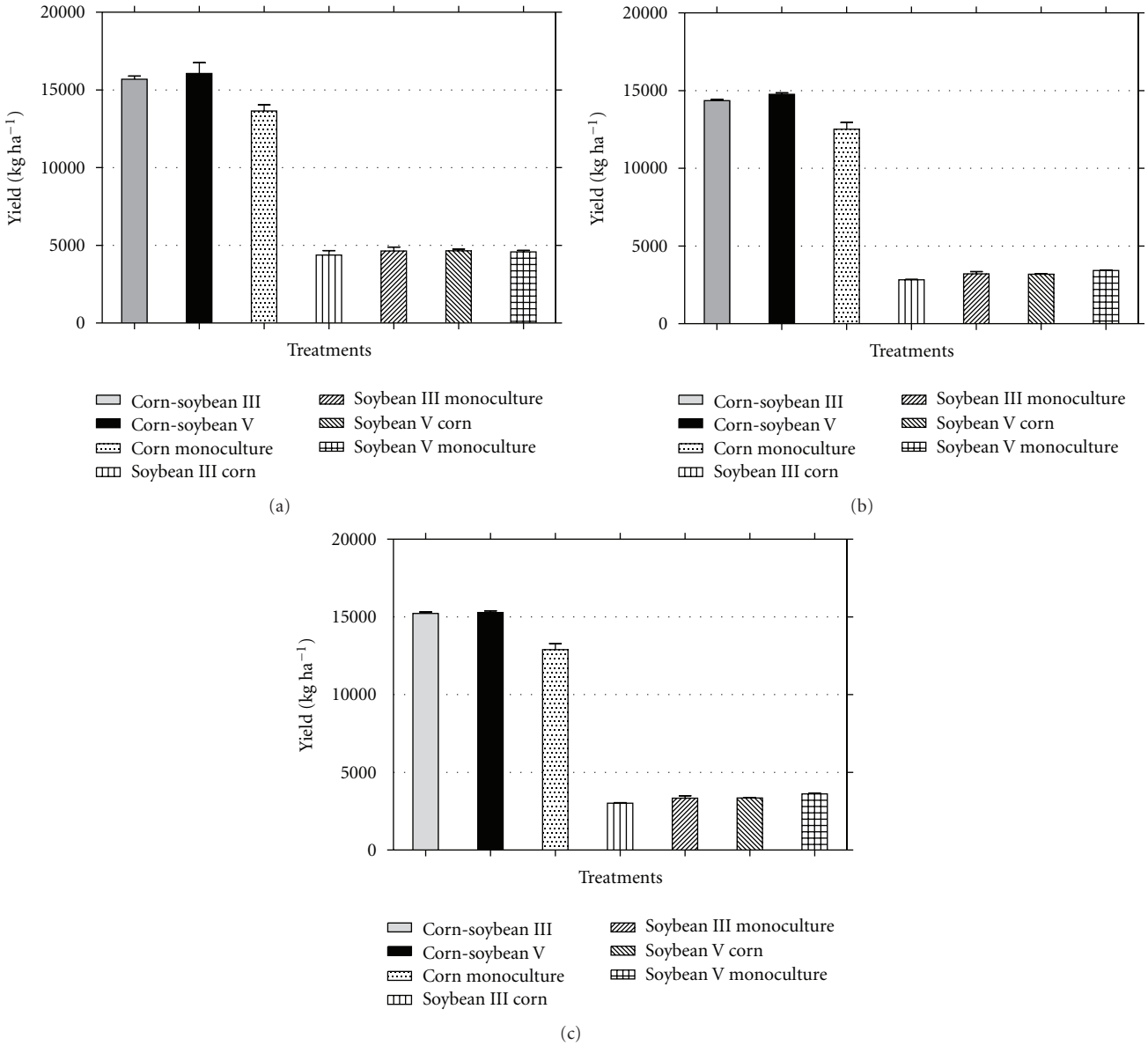

Figure 4: Crop yields in monocultures and in intercropped in C1 (a), C2 (b), and C3 (c).

of plants located in the inner rows (e.g., row 7) and plant located in the monoculture. This response was similar in each year with subtle variations depending on the accompanying soybean cultivar (Tables 1 and 2). Corn yield increased 13, 13, and 16% when cultivated with MG III soybean strip and 15, 15, and 16% with MG V soybean strip, during C1, C2, and C3, respectively (Figure 4). Results are similar to that obtained in USA [15, 16], China [17], and Argentina, [18, 19].

4.4. Grain Yield Components. GNUA of plants located in border rows (1 and 12) of the strip was higher than those located in the central row or in the monoculture in both corn-soybeans associations (Table 1), except in C1 in corn-soybeans MG III. This response may be explained by findings of Lesoing and Francis [20, 21] who reported that yield and its components increase as radiation interception increases. On the other hand, Andrade et al. [7] and also Fisher and Palmer [22] have reported that irradiance reductions around the critical period may reduce the crop yields by 50%, whereas filling reduction may reduce yields by 25%. In the three seasons, the highest GNUA values were achieved in plants located in outer rows (1 and 12) with highest IPAR (Figure 5).

This response was observed in both corn-soybeans strips. Results may be explained by findings of Maddonni et al. [23] who reported that when IPAR decreases at R1, it may account for up to 58% of GNUA reductions.

GNUA is a function of the growth rate during the flowering period (Andrade et al. [7]). Plants of outer rows

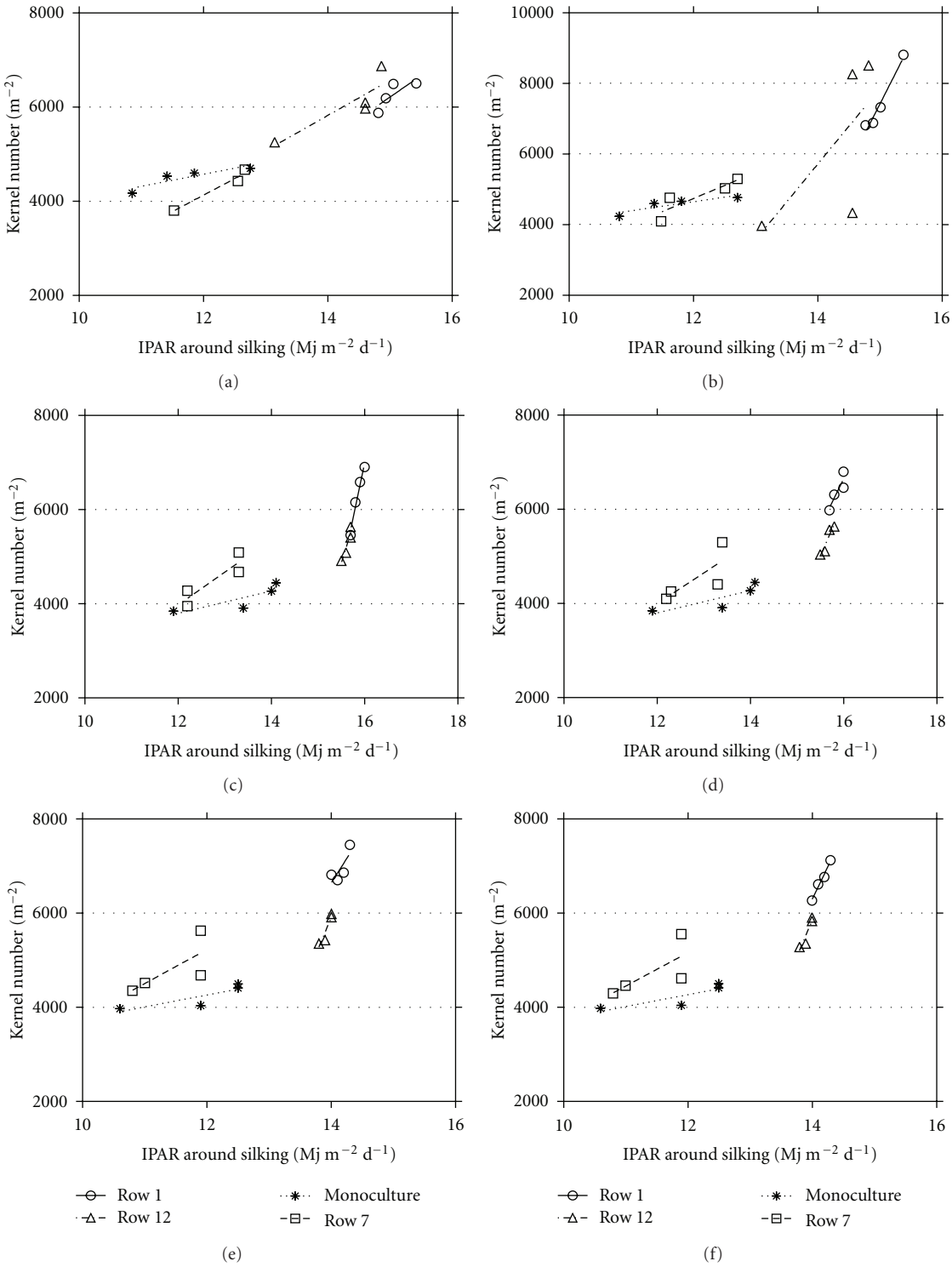

Figure 5: Number of corn grains per unit area in relation to IPAR around flowering in monoculture and in rows 1, 7, and 12 in corn-soybeans MG III strips, during C1 (a), C2 (c), and C3 (e) and in corn-soybeans MG V strips, during C1 (b), C2 (d), and C3 (f).

showed the highest CGR during the critical period, thus allowing a greater GNUA fixation. The decrease in the intercepted radiation was also correlated with the decrease in the GNUA, as has been found by Tollenaar et al. [24]; Kiniry and Knievel, [25]; Andrade et al. [5–7]; Maddonni et al. [23] in corn monocultures. The lesser response measured in C2 may be due to unfavorable water balance during crop cycle (Figure 6).

Both GNP and ENP showed similar tendencies, since plants of outer rows in the strip had higher values than those

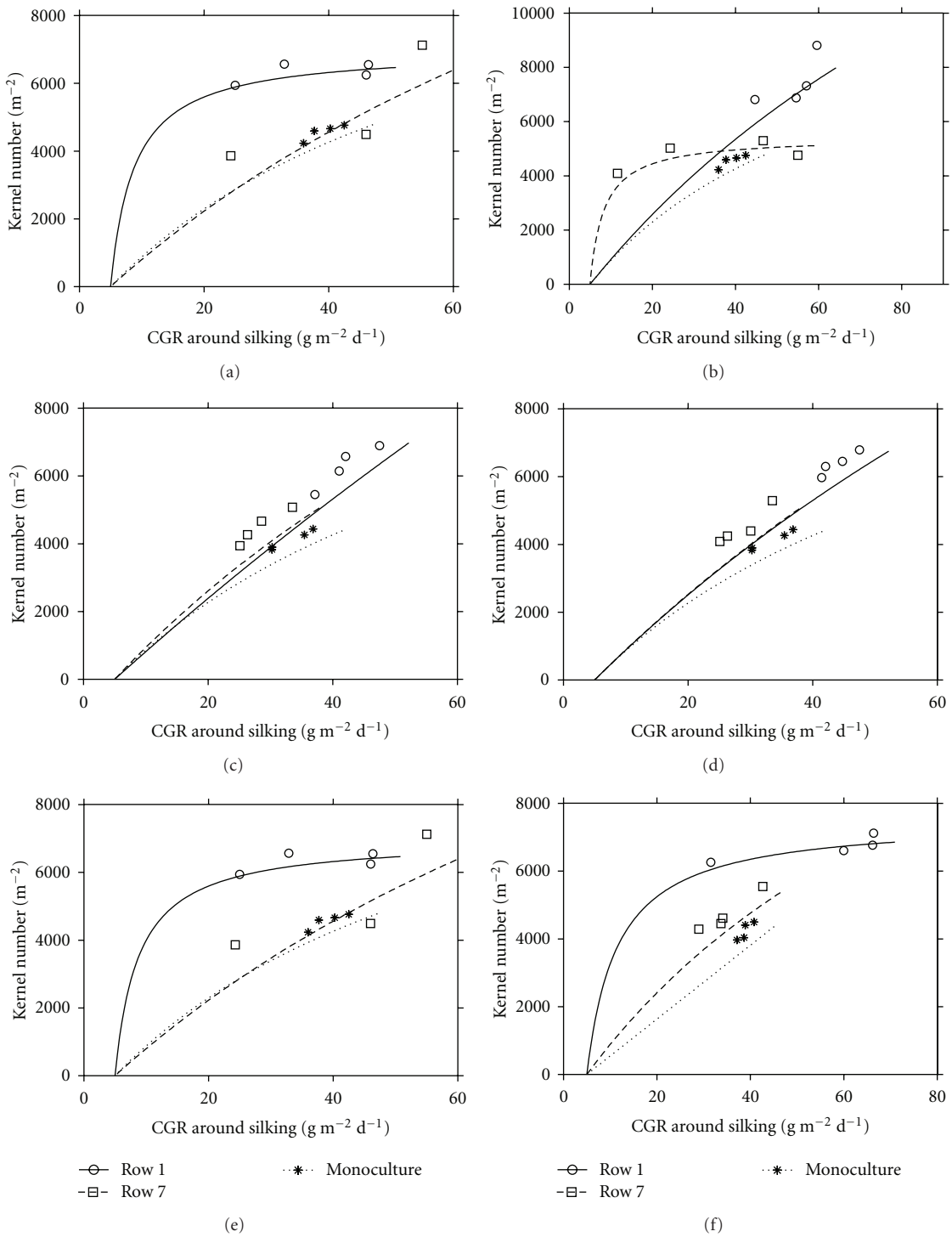

Figure 6: Number of corn grains per unit area in relation to crop growth rate around silking in the monoculture and in the strips 1 (border) and 7 (center) in corn-soybeans MG III strips, during C1 (a), C2 (c), and C3 (e), and of the corn-soybeans MG V strips, in C1 (b), C2 (d) and C3 (f).

of plants located in the center or in the monocultures. Plants of row 1 generated a second ear in 60% of the time of plants of row 1 and plants of row 12 generated a second ear 40% of the time (Table 3). Similar results were reported by Lesoing and Francis [20] and Ghaffarzadeh et al. [26].

As far as grain number per ear, which is related to ear size, there were no significant differences, as it has also been found by Lesoing and Francis [21] and Francis et al. [27]. A probable explanation to this response is that although water stress occurred in year C2, it may have not been significant

Table 3: Corn and soybean grain yield components and grain yield in monocultures and intercropped, during C1, C2, and C3. Ear number per plant (ENP, n° pl^{-1}), ear number per unit area (ENUA, n° m^{-2}), pods number per plant (PNP, n° pl^{-1}), pods per unit area (PUA, n° m^{-2}), 1000-grain weight (1000 GW, g), grain number per plant (GNP, n° pl^{-1}), and GNUA (n° m^{-2}), GY (kg ha^{-1}). Locations 1, 7, or 12 correspond to northern, central, and south rows, respectively. In the monoculture, the measurements were done at the center of the plot. Numbers in the same column followed by same letter are not significantly different ($P < 0.05$).

Treatment	Location (rows)	ENP (n° pl^{-1})			ENUA (n° m^{-2})			PNP (n° pl^{-1})			PUA (n° m^{-2})		
		C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
Strip corn/soybean III	1	1.5a	1.6a	1.6a	12.6a	14.8a	14.8a	—	—	—	—	—	—
	7	1.2a	1.2b	1.2b	9.8a	9.8bc	9.8bc	—	—	—	—	—	—
	12	1.6a	1.6a	1.6a	13.4a	13.4ac	13.4ac	—	—	—	—	—	—
Strip corn/soybean V	1	1.6a	1.6a	1.8a	15a	15a	16a	—	—	—	—	—	—
	7	1.2a	1.2a	1.2b	10b	10b	10b	—	—	—	—	—	—
	12	1.6a	1.6a	1.6ab	14ab	13ab	14ab	—	—	—	—	—	—
Corn monoculture	Center	1.2a	1.1b	1.1b	9.6a	8.4b	8.4b	—	—	—	—	—	—
Strip soybean III/corn	1	—	—	—	—	—	—	22d	20d	24d	777d	898d	648d
	7	—	—	—	—	—	—	39e	37e	38d	1541d	1360e	1438d
	12	—	—	—	—	—	—	30ab	26ab	28a	988d	872de	922d
Soybean III monoculture	Center	—	—	—	—	—	—	37e	34e	35d	1478d	1304de	1379d
Strip soybean V/corn	1	—	—	—	—	—	—	25d	24a	28a	1041d	924d	975d
	7	—	—	—	—	—	—	35de	33ab	34ab	1387d	1231d	1299d
	12	—	—	—	—	—	—	30de	27ab	28ab	1446d	1284d	1354d
Soybean V monoculture	Center	—	—	—	—	—	—	44e	41e	42e	1808d	1605d	1694d
Treatment	Locatio (rows)	1000 GW (g)			GNP (n° pl^{-1})			GNUA (n° m^{-2})			GY (kg ha^{-1})		
		C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
Strip corn soybean III	1	308a	316a	312a	474a	677a	699b	6325a	6267a	6956a	19456a	19754a	21669a
	7	292a	297a	294a	487a	628a	555ab	5052b	4488b	4792bc	14495b	13258b	13975b
	12	323a	330a	325a	425a	649a	640a	6108ac	5252c	5667c	19646a	17267a	18385c
Strip corn soybean V	1	317a	328a	324a	799b	686ab	719b	7454a	6377a	6686a	23546a	20916a	21669a
	7	307a	301a	298a	554ab	531a	524bc	4792b	4505b	4724b	14750b	13490b	13975b
	12	315a	334a	330a	694ab	639ab	646ab	6264a	5328b	5587b	19454a	17746c	18385c
Corn monoculture	Center	299a	305a	301a	514a	554a	519a	4561c	4108c	4288c	13636b	12520b	12898b
Strip soybean III corn	1	172b	165b	167b	—	—	—	1850d	1400d	1440d	3169d	2314d	2406d
	7	170b	166b	168b	—	—	—	2940d	1800ef	1860de	5013d	2994e	3116e
	12	170b	168b	163b	—	—	—	2110d	1600df	1720de	3583d	2678f	2788f
Soybean III monoculture	Center	162b	160b	167b	—	—	—	2870d	2010e	2010e	4633d	3205e	3336e
Strip soybean V corn	1	172b	165b	167b	—	—	—	2130d	1410d	1440d	3655d	2317d	2412d
	7	170b	166b	168b	—	—	—	2550d	2170e	2260e	4312d	4312e	3793e
	12	170b	168b	163b	—	—	—	2300d	1640de	1770de	3905d	3905f	2897f
Soybean V monoculture	Center	162b	160b	167b	—	—	—	2820d	2150e	2180e	4566d	4566e	3612e

during the grain filling period. Previous experiments report contrasting responses on the water stress on this yield component [20, 21, 26, 28, 29]. It is important to note that two weeks following crop blooming, the young grain does not accumulate dry weight. Instead, a great mitotic activity occurs, responsible for determining the number of cells of the endosperms and also the starch granules [30]. Unfavorable conditions during this stage not only reduce the endospermatic cells, but also the number of starch granules, thereby affecting the grain size potential [31, 32]. After the above-mentioned stage, grain growth is linear and increases up to 90% of final weight. At this stage the grain weight gain is linearly positively correlated to air temperature [33, 34].

5. Soybeans

5.1. Irradiance. The IPAR in row 1 was significantly lower than those in the central and twelfth rows and also than those in the monocultures. Reduced IPAR values were evident once the corn plants in the adjacent rows surpassed stage V6 (70 cm height). The shading effect extended its influence to the three nearest consecutive rows of soybeans. The radiation received in the further soybean rows was not affected by the corn strip (Table 1).

5.2. IPAR and CGR. The highest IPAR levels were registered in the central row of the strip and also in the center of the monoculture. This high IPAR allowed the highest CGR in all cases. In soybeans MG III-corn, IPAR was 10 Mj m^{-2} d^{-1} and CGR 20 was g m^{-2} d^{-1}, during C1 and C3, and 15 g m^{-2} d^{-1}, during C2. Within row 7 and also in the monoculture IPAR approached 14 Mj m^{-2} d^{-1} and CGR ranged from 20 to 60 g m^{-2} d^{-1}, in C1 and C3, and from 15 to 25 g m^{-2} d^{-1}, in C2 (Figure 7). The responses in soybeans MG V-corn followed the same tendency: highest IPAR levels approached 14 Mj m^{-2} $d^{-1}$and CGR surpassed 50 g m^{-2} d^{-1}.

5.3. RUE. RUE in soybeans ranged from 0.5 to 1.2 g Mj^{-1} in the three seasons. Differences were detected in the strip plots as compared to that in the monocultures (Table 2, Figure 8).

5.4. Grain Yield. During C1, there were no differences in between yield between any row in either of the maturity groups. During C2 and C3, in both soybean cultivars, yields in rows 1 and 12 significantly differed to row 7 and to monoculture (Table 3).

Average yields of soybean strips MG III were 6, 13, and 11% lower than those in the monoculture, whereas in MG V yields were 2, 8, and 8% lower than those in the monocultures during C1, C2, and C3, respectively (Figure 4). Results are similar to those obtained by Pendleton et al. [35], Lesoing and Francis, [20, 21], West and Griffith, [15], Ghaffarzadeh et al. [16], and Francis et al. [27].

5.5. Grain Yield Components. GNUA was significantly lower in plants located in rows 1 and 12, as compared to that of the plants located in the central row and those in the monoculture. This response was almost identical in both soybean cultivars (Table 3).

A possible explanation of this response may be found by looking at the reduction in IPAR and in CGR of plants located in rows 1 and 12 during the critical period. Figure 9 shows the positive relationship among the GN and IPAR: in almost the entire crop growth cycle, row 1 had lower GN, probably due to a lower IPAR accumulation, due to the shade caused by the nearby corn plants.

On the other hand, plants in row 12 had lower GN. Since shading effect occurred because the corn was located on the southern side of the strip, any explanation is available for this result. GN values of plants in the central row were similar to those of row 12. Overall responses observed, however, are in close coincidence to those determined by Fehr and Caviness [36] who proposed a positive relationship among GN and accumulated IPAR from R3 to R6. Thus, the longer the duration of this critical period, the increased IPAR [13].

The enhanced IPAR allowed an increased CGR, which may have contributed to the increase in GNUA in plants located in row 7 and also in the monoculture, as compared to that in row 1. Observed responses were similar in both maturity groups (Figure 10).

GNUA was higher in MG V than in MG III. Since resource overlapping is a major issue when searching for the explanations in the performance of two species [37], (Table 3), a possible explanation of different responses may be found by looking at their critical periods (R3–R6, [36]). The critical period for MG may have been less overlapped with corn's critical period than MG III.

PNP and PUA were significantly lower in the plants located in rows 1 and 12 as compared to those of plants located in the center of the strip and also to that in the monocultures (Table 3). As for corn, any statistical differences were found in GW (Table 3).

6. Conclusions

Corn plants increased their yield in border rows when grown next to soybeans. Increased yield was closely correlated to increased radiation interception which allowed an increased crop growth rate around the critical period (R1), thus increasing dry matter partition to the grains. The increased IPAR in plants of border rows, associated to an increased CGR, also boosted the differentiation of greater number of ears and consequently greater grain number per plant. These yield subcomponents explained the increased number of grains per unit area.

In soybeans, there were no clear advantages when grown next to corn. Those plants growing in the borders next to corn plants reduced their yield compared to those of the monocultures, however only significantly in MG III. The yield component closely associated to yield reduction was GNUA.

Our experiments contribute to the explanation of the observed increased corn yields and the limited penalties of soybean genotypes grown in strips. The increased availability of new corn and soybean genetically modified genotypes, coupled to new herbicides and machinery technologies, may allow expanding this crop technique to broader areas and/or to different crop sequences and/or crop associations. If yield components affected are more closely identified, every single actual crop production system may be improved by selecting more appropriate genotypes to be used in strip intercropping, thus contributing to the sustainability of our agricultural systems.

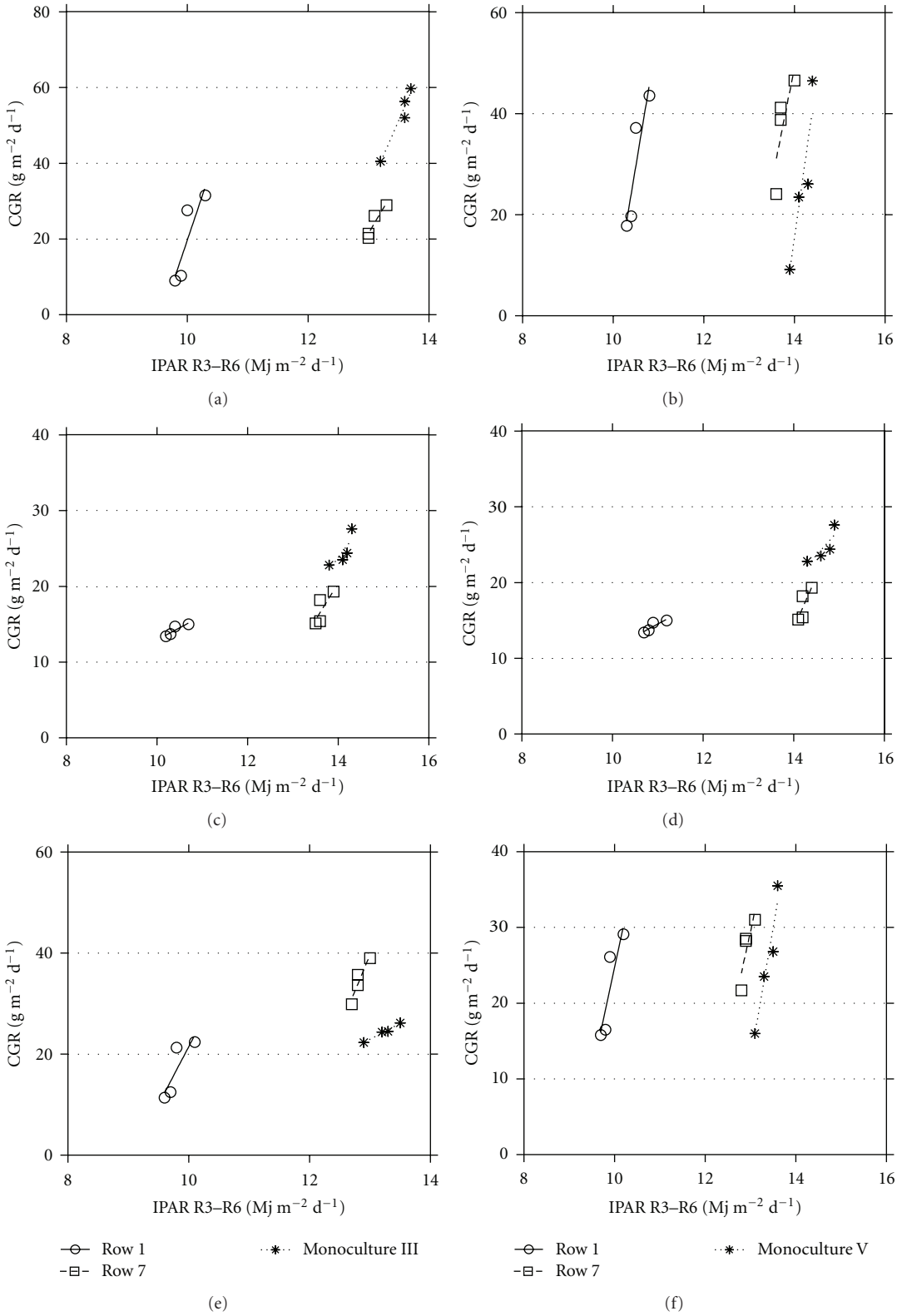

Figure 7: CGR within the period R3–R6 as a function of IPAR in the monoculture and in rows 1 and 7 of soybeans MG III-corn strips, during C1 (a), C2 (c), and C3 (e) and of soybeans MG V-corn strips, during C1 (b), C2 (d), and C3 (f).

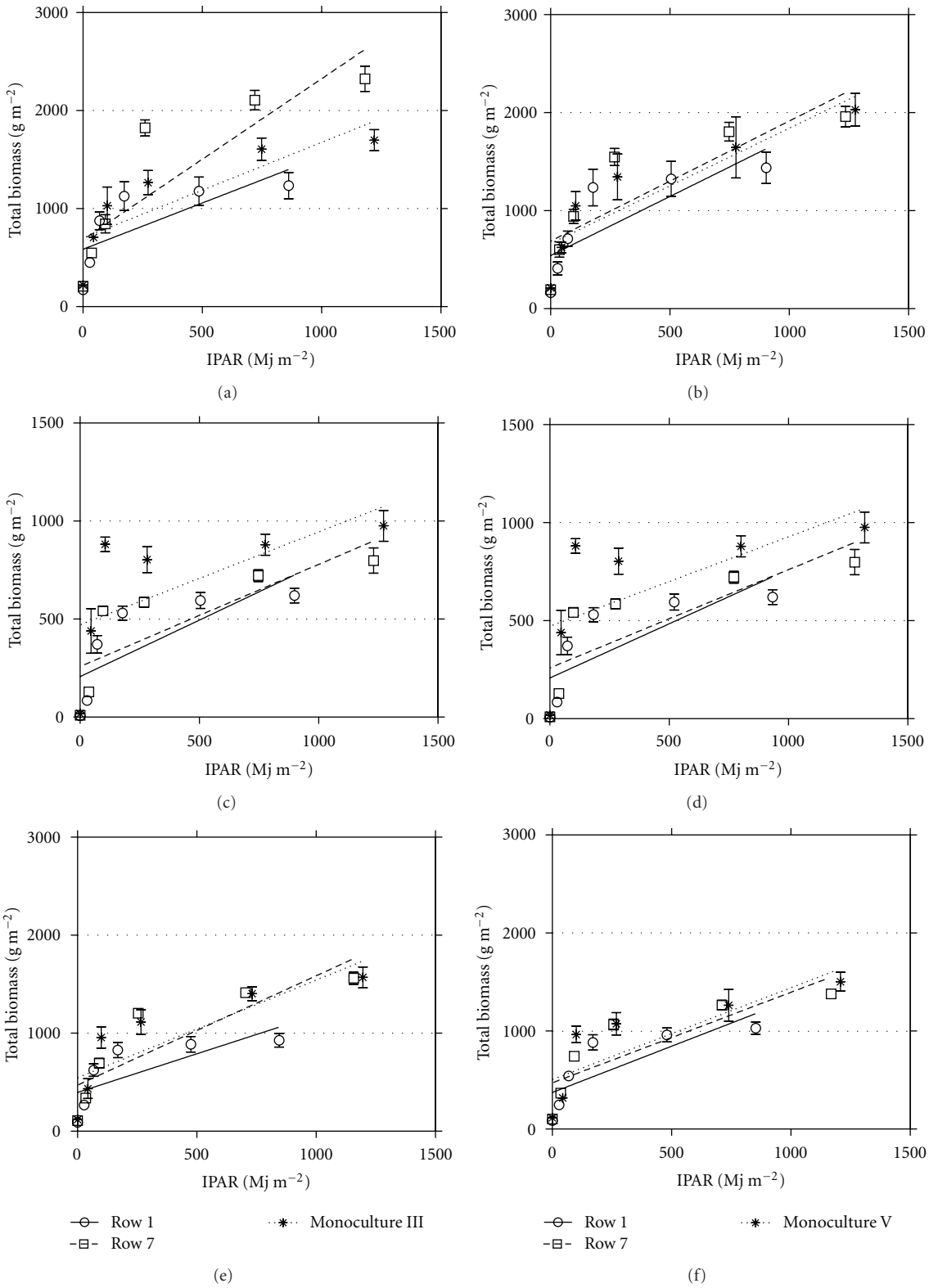

Figure 8: Total biomass versus IPAR in rows 1 and 7 of strips and in the monoculture, during C1 (a) and (b), C2 (c) and (d) and C3 (e) and (f). (a), (c), and (e) correspond to soybeans MG III, and (b), (d), and (f) to corn-soybeans MG V.

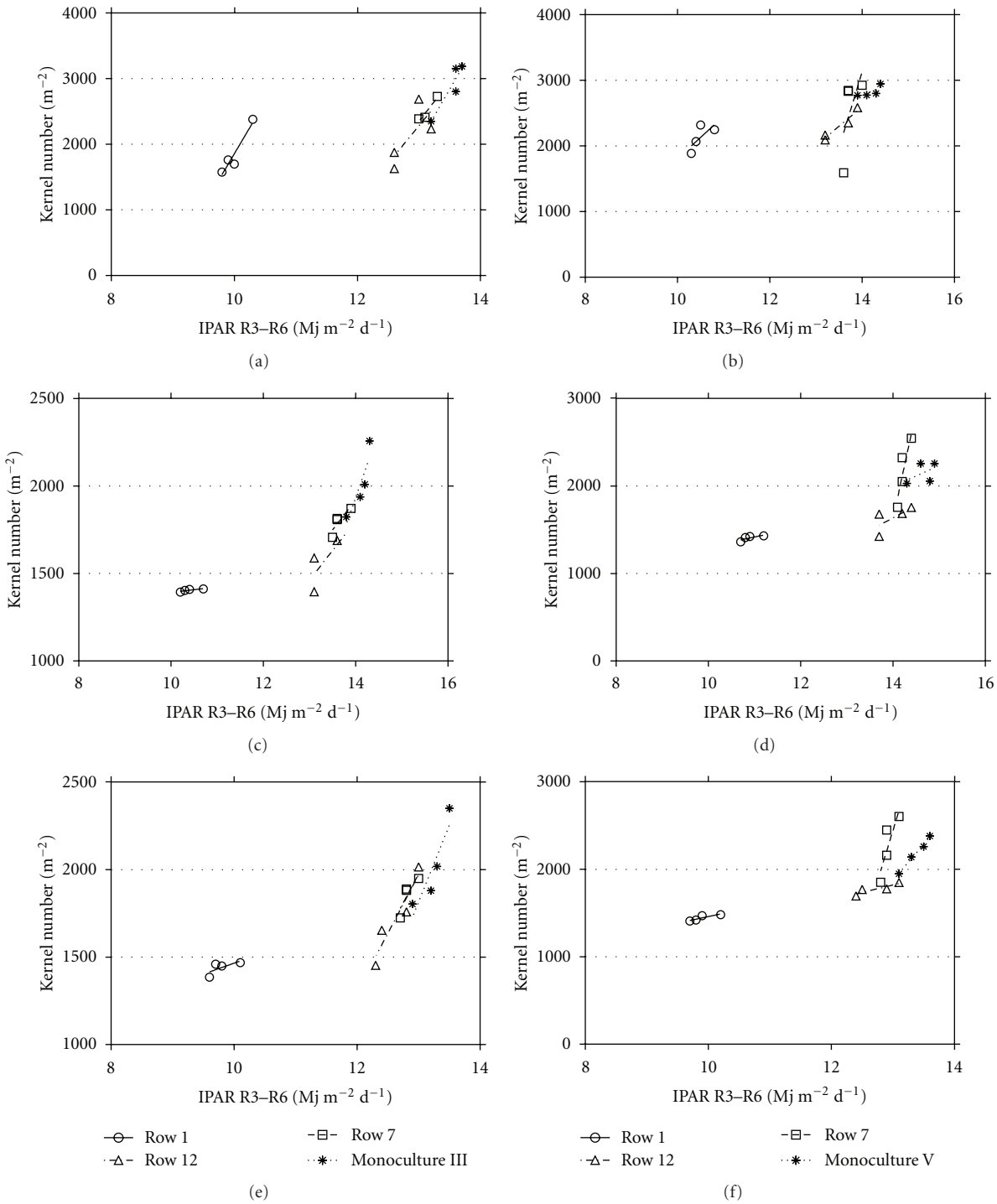

Figure 9: GNUA in relation to IPAR within R3–R6 in monocultures and in the strips in row 1, 7 and 12 of soybeans MG III-corn strips during C1 (a), C2 (c), and C3 (e) and in soybeans MG V strips during C1 (b), C2 (d), and C3 (f).

Acknowledgments

Technical expertise of J. R. Pérez for collecting and processing plant data is gratefully recognized. The willingness of the owner of the farm, Mr. G. Verdelli, where experiments were done, is also fully appreciated. Experiments were partially funded by several technical services made to agrichemical companies and are part of the research project of ESL. Suggestions and corrections made by referees and editor are gratefully acknowledged.

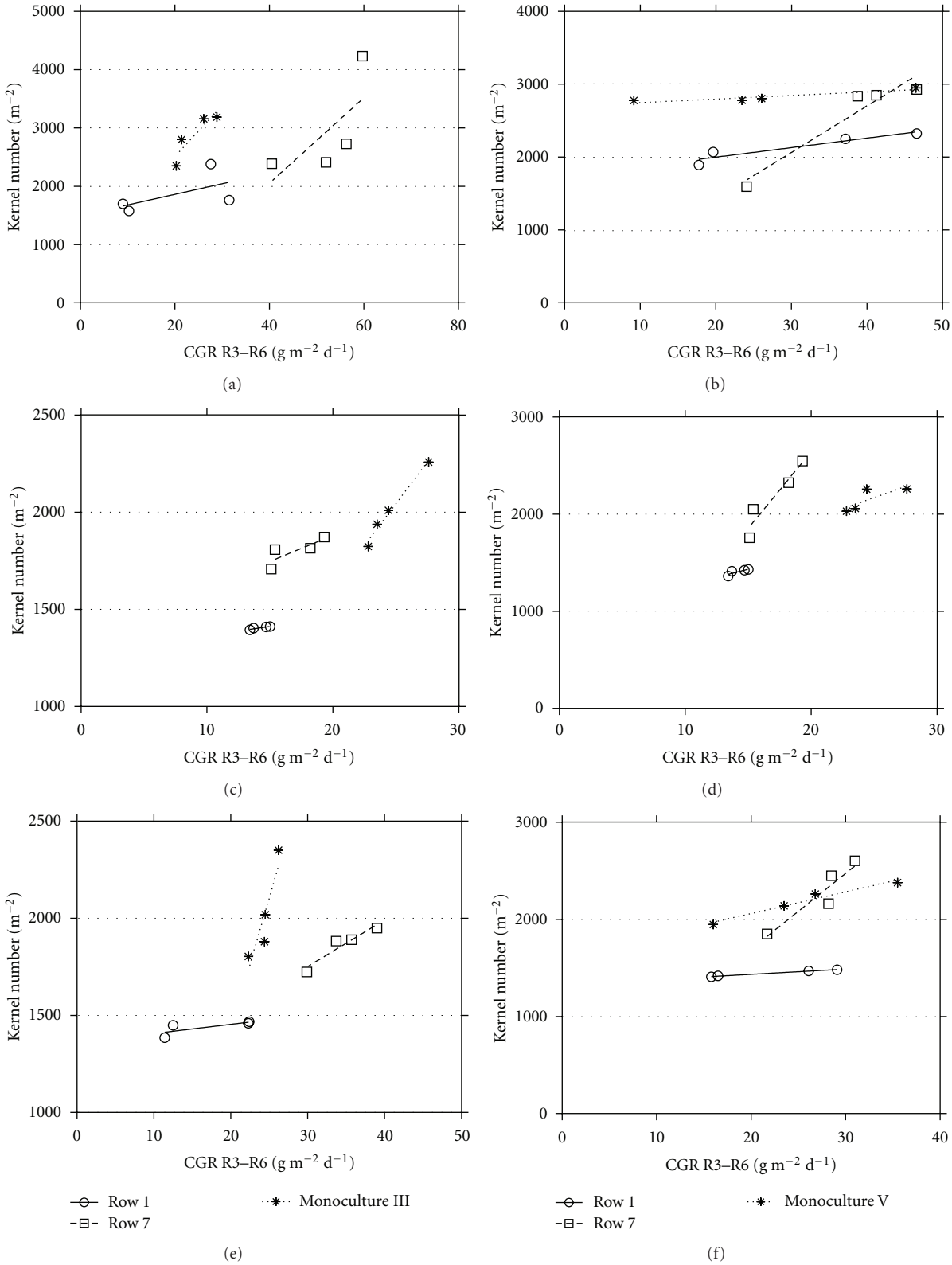

Figure 10: GNUA related to CGR within R3–R6 in monoculture and in the rows 1 and 7 (center) of soybeans MG III-corn strips during C1 (a), C2 (c), and C3 (e) and in soybeans MG V-corn strips during C1 (b), C2 (d), and C3 (f).

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