

Can productivity and post-pruning growth of *Jatropha curcas* in silvopastoral systems be regulated by manipulating tree spacing/arrangement without changing tree density?

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Abstract

The potential of tree spacing/arrangement to alleviate effects of interspecific competition of hedgerow intercropping systems on productivity and response to pruning of *Jatropha curcas* was investigated using a *Jatropha curcas* - *Pennisetum clandestinum* (kikuyu) silvopastoral system at Ukulinga (KwaZulu Natal, South Africa). Treatments were differentiated by presence/absence of kikuyu and arrangement/spacing of *Jatropha* trees (one, two and three tree hedgerows on either side of the alley) and had the same tree density (1110 ha⁻¹). When high water availability and kikuyu dormancy coincided, tree growth rates did not significantly differ across treatments. Trees of the treatment without interspecific competition (tree-only) were the tallest. Even when rainfall was high, post-pruning tree height growth rate was affected by belowground (BG) interspecific competition and tree spacing/arrangement. Treatment with a single tree hedgerow between alleys had the most frequent maximum stem growth rate and was the most efficient during limited water availability. Its trees showed slow initial response to pruning due to a high tree-grass interface, followed by compensatory growth when competition for water with grass was low. Generally, length of tree-grass interfaces affected yield inversely especially as trees matured toward their maximum-yield age (4-5 years). BG competition reduced tree

yield more than tree biomass, while tree spacing/arrangement did not affect tree harvest index. Manipulation of tree arrangement/spacing without changing tree density had no consistent effects on tree productivity.

Keywords *Jatropha* growth rate, interspecific competition, post-pruning growth, tree-grass interface

Research highlights

- Interspecific competition reduced *Jatropha* productivity and post-pruning growth.
- Tree spacing had significant effects on post-pruning growth of *Jatropha*.
- Effects of tree spacing on growth and yield of *Jatropha* were inconsistent.]

1 INTRODUCTION

Tree hedgerow intercropping systems cover roughly 60 % of the land under agroforestry, occupying mainly humid and sub-humid tropical and temperate (North America, Canada Europe) regions [1, 2]. It can take other forms, including silvopastoral, silvoarable, agrosilvopastoral (crops/timber/livestock), multi-level plantations (fruit/timber/crops) and agrisilvicultural (crops/timber) [3]. More than a single row of trees (sets of two or three rows) may be employed in order to possibly minimise reductions in tree productivities and maximise earnings [4] by optimizing intraspecific and interspecific interactions in the system.

Jatropha curcas L., (henceforth referred to as *Jatropha*) has been investigated under agroforestry systems. It is a small (up to 6 m tall), deciduous, poisonous, fast-growing tree belonging to the family Euphorbiaceae. It originated from Mexico and Central America and is widely distributed in the tropical and sub-tropical Africa and Asia [5]. It grows well within altitude and temperature ranges of 0 to 1 800 m (prefers below 500 m) and 11.0 to 28 °C respectively [6, 7]. Under favourable conditions, *Jatropha* matures to full productivity as early as 3 to 4 years after planting [5]. It is highly adaptable to arid and semi-arid conditions [8], requiring annual rainfall amount of at least 250 mm. It can grow on heavy to well-drained soils and soils with poor fertility. It tolerates mild frosts [9] but is not affected by day-length [8].

Jatropha is a multi-purpose tree. Most prominently, it is a source of bio-diesel rich seeds [6, 10], containing high concentration of highly extractible oil [11]. The oil produces minimal smoke and engine wear and has better efficiency than diesel [6, 12] in its pure, mixed and biodiesel forms [7, 8, 10]. Other applications of *Jatropha* or its parts include for erosion control, live-fencing against browsing animals [5], poles and fence posts [13]; making soaps, pesticides and insecticides [7] and for medicinal applications [12].

The objectives of this study were to examine: nature (competitive or complementary) of BG interactions between *Jatropha* and kikuyu, a perennial grass, in a rain-fed hedgerow intercropping system by studying their effects on vegetative and reproductive tree productivities; and feasibility of alleviating competitive tree-crop interactions by manipulating spacing/arrangements *Jatropha* trees while keeping tree density constant. *Jatropha* was selected as a high-value and drought tolerant tree that can grow on low fertility soils. Since *Jatropha* is not consumed by browsing animals, its productivity in silvopastoral systems is not compromised by such animals. Kikuyu was selected due to its high capacity as a grazing pasture even under dryland. The *Jatropha*-Kikuyu system could potentially improve livelihood of small-scale farmers as a source of pasture (kikuyu) and income through the sale of *Jatropha* seeds.

Two hypotheses were formulated:

1. BG interactions between *Jatropha* trees and a perennial grass in hedgerow intercropping systems in semi-arid areas are predominantly competitive, resulting in reductions of growth and yield of the trees
2. For a given tree density in hedgerow intercropping, tree spacing/arrangement can be optimised in order to reduce BG competition and minimise growth and yield reductions of the *Jatropha* trees.

2 MATERIALS AND METHODS

2.1 Treatments

The hedgerow intercropping system where the current study took place was a rain-fed silvopastoral system at the Ukulinga Research Farm of the University of KwaZulu Natal, Pietermaritzburg Campus, South Africa (30° 24' S, 29° 24' E). Ukulinga has mean annual rainfall of 680 mm and an altitude of 781 m above sea level. Summers are warm to hot and winters mild with frosts rarely occurring. Mean annual temperature is 18.4 °C

[14]. The soil type at the site is a loam (21.1 % clay, 37.1 % silt and 41.8 % sand) to clay loam (30.2 % clay, 34.5 % silt and 35.3 % sand) with organic matter content of 1.28 % ($cv = 69.8$ %).

The study site was divided into a number of plots to accommodate various trials involving *Jatropha* and kikuyu (*Pennisetum clandestinum*). The plots were 50 m by 25 m. Tree planting density was 1110 ha⁻¹. Five treatments arranged in a randomised-block design with three replicates and differentiated by presence/absence of kikuyu and spacing/arrangement of *Jatropha* trees were used. They were: *Jatropha*-only or control (JO, 3 m x 3 m); standard-spacing (SS, 3 m x 3 m); single-row (SR, 5 m x 2 m); double-row (DR, 6 m x 2 m x 2.5 m); and triple-row (TR, 7 m x 2 m x 3 m). Details of set up of the treatments are presented in Figure 1 and Table 1. During each growing season, recommended amounts of Nitrogen (200 kg ha⁻¹), Phosphorous (20 kg ha⁻¹) and Potassium (100 kg ha⁻¹) were applied to the treatments (based on soil analyses).

Table 1 Characteristics of tree-grass (T-G) interface and area occupied by trees only in the treatments of the hedgerow intercropping system at Ukulinga research farm

Treatments	T-G interface (m)	System-area (m ²)	T-area System-area (%)	T-G interface T-area (m m ⁻²)	T-G interface System-area (m m ⁻²)
JO	0	9	100	0	0
SS	4	9	11.11	4	0.44
SR	4	10	20	2	0.40
DR	2.5	20	18.75	0.67	0.25
Outer rows	3 m		13.64	0.67	0.18
TR Centre row	0 m	33	18.18	0	0
Mean	2		15.13	0.13	0.06

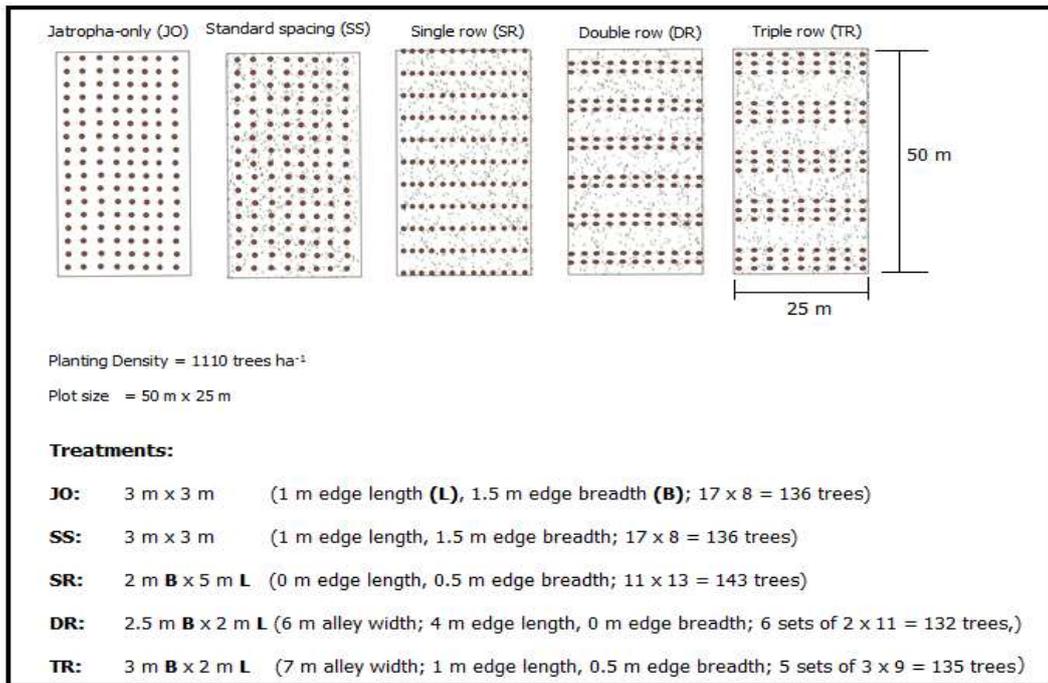


Figure 1 Plot details: JO, SS, SR, DR and TR at Ukulinga research farm **Table 1**

In Table 1, system-area refers to the area between the midway of alleys on either side of a tree set and half the intra-row spacing on either side of a tree in a row; T-area refers to the grass-cleared area around a tree (and occupied by the tree only) divided by system area; the ratios T-G interface to T-area and T-G interface to system-area are implicit indicators of the intensity of BG interspecific interactions; and weighted mean of T-G interface in TR was calculated as:

$$\text{Mean length T-G interface (m)} = (33.3 \% \times 3) + (66.7 \% \times 0) = 2 \text{ m} \quad 1$$

Where: 33.3 % represents the five centre rows in a plot having T-G interface length of 0 m and 66.7 % the 10 outer rows in a plot, which had T-G interface length of 3 m.

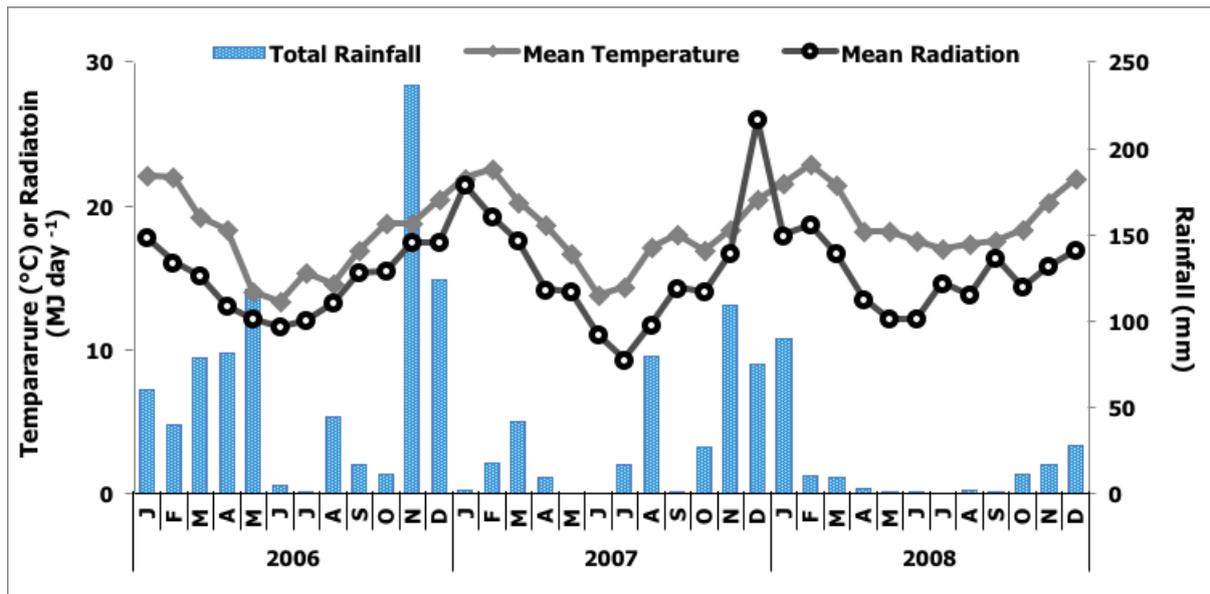


Figure 2 Monthly values of total rainfall, mean temperature and solar radiation at the Ukulinga during the study period

2.2 Sampling

2.2.1 Treatment effects on *Jatropha* growth

Basal stem diameters of 30 trees from each of the 15 plots (5 treatments x 3 replicates) were monitored monthly between June 2006 and August 2008 to examine treatment effects on growth rate of stem diameter. The trees were 18 month-old at the beginning of the monitoring.

All trees in the 15 plots were top-pruned to a height of one metre in September 2007 in order to stimulate additional branching for increasing seed production and for maintaining the trees as hedgerows. The pruning method was in accordance with several *Jatropha*-related studies [5, 15, 16]. Tree heights of 30 trees from the plots were monitored monthly from October 2007 to May 2008 to examine effects of the treatments on post-pruning growth rate of tree height.

2.2.2 Treatment effects on yield and harvest index on *Jatropha*

Ready-to-harvest *Jatropha* seeds were picked from the 15 plots between April and August of 2007, 2008 and 2009 to study what effects treatments had on seed yield of *Jatropha* trees. These yields represented 2006/07, 2007/08 and 2008/09 growing seasons respectively.

End-of-April basal stem diameter measurements of 30 sample trees were taken from each plot for the 2006/07 and the 2007/08 growing seasons. These data were used in conjunction with yield data to investigate effects of treatments on harvest index of *Jatropha* trees.

2.3 Calculations and data analyses

2.3.1 Calculations

Treatment effects on stem growth rate

Diameter data from treatment replicates were used to calculate seasonal relative growth rates (RGR) of basal stem diameter (D) using the equation:

$$\text{RGR (\%)} = 100 [(D_2 - D_1) / m] (t_1 - t_2)^{-1} (D_1^{-1} / m) \quad 2$$

Where: D_1 and D_2 represent diameter at times t_1 and t_2 respectively.

Seasonal growth rates were approximated using monthly data, as grouped as:

- Winter: June, July and August;
- Spring: September, October and November;
- Summer: December, January and February; and
- Autumn: March, April and May.

Seasonal RGR values of all treatment replicates were determined for winter 2006 to autumn 2008.

Treatment effects on post-pruning height increase of *Jatropha*

Monthly tree heights from all treatment replicates were used to calculate monthly post-pruning height RGR using equation 1, by replacing D_1 and D_2 with tree height H_1 (at t_1) and H_2 (at t_2) respectively.

Treatment effects on tree yield

Total dry seed harvest from treatment plots was divided by the number of trees in the plots (Table 1) to obtain average yield per tree.

Treatment effects on harvest index

Harvest index shows if tree-crop (T-C) competition or tree spacing/arrangement in hedgerow intercropping affect tree yield more (or less) than tree growth. Plot average of end-of-April stem diameters were used to estimate average AG *Jatropha* biomass using an equation of total AG dry mass of *Jatropha* [17]:

$$(\text{AG biomass/g}) = 9.07 \times 10^{-4} (\text{stem diameter/m})^{3.354} \quad 3$$

Yield and AG biomass of individual trees were used in equation 4 to compute harvest index (HI) of plots:

$$\text{HI (\%)} = 100 (\text{Seed yield/g}) (\text{AG biomass}^{-1}/\text{g}) \quad 4$$

This procedure was carried out for 2006/07 and 2007/08 seasons.

2.3.2 Data analyses

Treatment effects on stem growth rate

Seasonal RGR values of all treatment replicates were determined for winter 2006 to autumn 2008. Analyses of variance were carried out using SAS Proc NLIN [18] to examine if growth rate of stem diameter was affected by presence of perennial grass, tree spacing/arrangement.

Treatment effects on post-pruning tree height increase

Monthly height RGR values treatments were statistically compared using SAS to test if post-pruning height growth was affected by BG tree-grass competition and tree spacing/arrangements.

Treatment effects on tree yield

Tree yields of treatments for 2006/07, 2007/08 and 2008/09 growing seasons were statistically analysed to examine if BG competition, and tree spacing/arrangement in hedgerow intercropping systems reduced tree yield.

Treatment effects on harvest index (HI)

Harvest indices of treatment were statistically compared using SAS [18] to examine what effect BG trees-grass interactions and tree spacing/arrangement had in the ability of the trees to produce yield per unit above-ground (AG) biomass.

3 RESULTS AND DISCUSSION

3.1 Effects of treatments on stem growth rate

Mean diameter of all treatments for the duration of the study are presented in Figure 3. Stem diameter was the highest in JO. When the trees were transplanted in January 2005 (during trial establishment), they had a stem diameter of approximately 10 mm. By January 2006, stem diameter in JO had increased to 56 mm. This was 19 % larger than the biggest diameters in other treatments. Such a difference was in agreement with numerous studies [13, 19, 20]. In January 2007 and January 2008, the difference was 13 % in favour of JO. By January 2009, stem diameters of JO trees were at least 18 % bigger than stem diameters in the tree-grass competition treatments. The fluctuations in stem diameter differences between control and treatments implied that the latter had relatively higher growth rates than the control treatment at times. It also indicated that tree-tree interactions in the system had little effect on tree growth compared to the tree-grass competition. Maximum stem growth of all treatments (sharp increases of diameter in Figure 3) coincided with the highest rainfall period during the study period, which was in November and December 2006 (Figure 2). This showed water availability was the main determinant for growth performance of trees in all treatments.

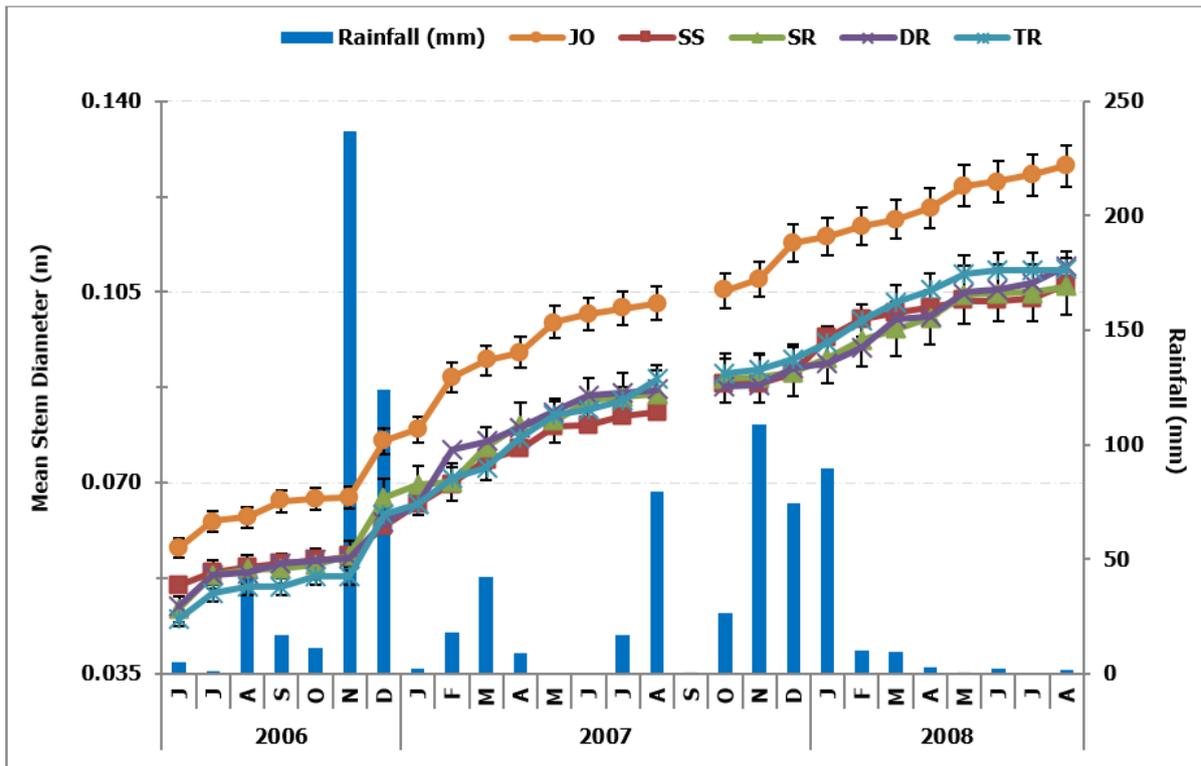


Figure 3 Mean stem diameter (m) of *Jatropha* trees in JO, SS, SR, DR and TR

Due to low rainfall, temperature and solar radiation, overall growth and development of *Jatropha* trees during winter was limited. One notable growth, however, was stem diameter. All treatments showed very high diameter growth rates during winter 2006 when all trees were entirely leafless, even though rainfall during January to May 2006 was very high. This resulted from stem photosynthesis, which is especially significant when trees are leafless [21, 22, 23, 24, 25]. Stem photosynthesis has considerable net-to-gross productivity ratios [26] and thus has significance in the carbon balance of trees [27]. In our study, tree height growth had slowed during winter 2006. Stem was the main assimilate sink, which was the strategy of *Jatropha* trees during poor growing conditions and minimum BG competitions (when kikuyu was dormant). Similar winter growth was not repeated in any treatment during winter 2007 and 2008 as rainfall during April and May of 2007 and 2008 was not as high as in 2006.

During winter 2006, treatments had no significant effects on tree RGR (Table 2). This may be due to the absence of BG interspecies competition due to kikuyu dormancy. It also implied that tree spacing/arrangement did not have any effect on diameter RGR. As kikuyu started to re-grow early in spring, differences among tree

RGRs started to occur. Trees in SS showed the highest growth rates (Figure 4) while trees of JO and TR had the lowest rates (Table 2). By December, growth in the treatments that had faster spring RGRs slowed, with trees from JO, SR and TR growing at higher rates than trees of SS and DR. In autumn, the treatments showed no significant differences in stem growth rates.

Table 2 Results of statistical analyses on seasonal stem RGR (%) during 2006/07 and 2007/08

Treatment	2006/07				2007/08			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
JO	6.83 ^b	1.90 ^c	10.29 ^a	4.24	1.27 ^c	1.43 ^{ab}	1.31 ^a	0.57 ^b
SS	4.94	3.75 ^a	7.21 ^b	4.86	1.39 ^c	2.22 ^a	1.40 ^a	0.68 ^b
SR	6.57	2.72 ^b	10.09 ^a	3.81	3.85 ^a	0.87 ^b	1.13 ^{ab}	1.29 ^a
DR	6.30	3.20 ^b	7.44 ^b	3.88	1.17 ^c	0.73 ^b	0.95 ^b	1.17 ^a
TR	6.64	1.59 ^c	11.05 ^a	5.04	2.62 ^b	1.19 ^b	1.43 ^a	0.70 ^b
Significance	Ns	**	**	Ns	**	**	**	**
LSD_{0.05}	2.41	0.52	1.82	1.37	0.60	0.94	0.34	0.16
CV	13.67	6.96	10.54	11.09	10.33	25.79	9.73	6.62

^β Values followed by the same letter within a column are not significantly different

* Significant at $p = 0.01$; ** Significant at $p = 0.05$; Ns = non-significant

During winter 2007 to autumn 2008, SR had significantly and consistently higher growth rates than SS and JO. During spring and summer of 2007/08, SS had the highest growth rates. TR showed high RGR during spring but slowed down by summer.

When rainwater was sufficiently available, winter and autumn seasons were characterised by RGRs that were not affected by treatments. During limited rainfall, on the other hand, treatments had differing RGRs based on their efficiencies of competition for water. SR was the most efficient while JO and SS were the least efficient. During spring 2007 and summer 2007/08, SS and JO had consistently the highest diameter RGR. The same result was observed for SS, during spring 2006. This treatment had the longest tree-grass (T-G) interface and the highest T-G interface per tree area (Table 1), which showed that trees in SS faced the strongest competition from kikuyu for resources especially water. When rainfall was sufficient, trees of this treatment had the highest growth rates, possibly to make up for the lag. A similar T-G interface length and T-G interface to tree area ratio in SR trees resulted in increased RGRs during limited interspecific competition periods (due to kikuyu dormancy and high rainfall). Despite achieving the highest stem diameter during the entire study period, trees in JO did not always have the highest consistent growth rate.

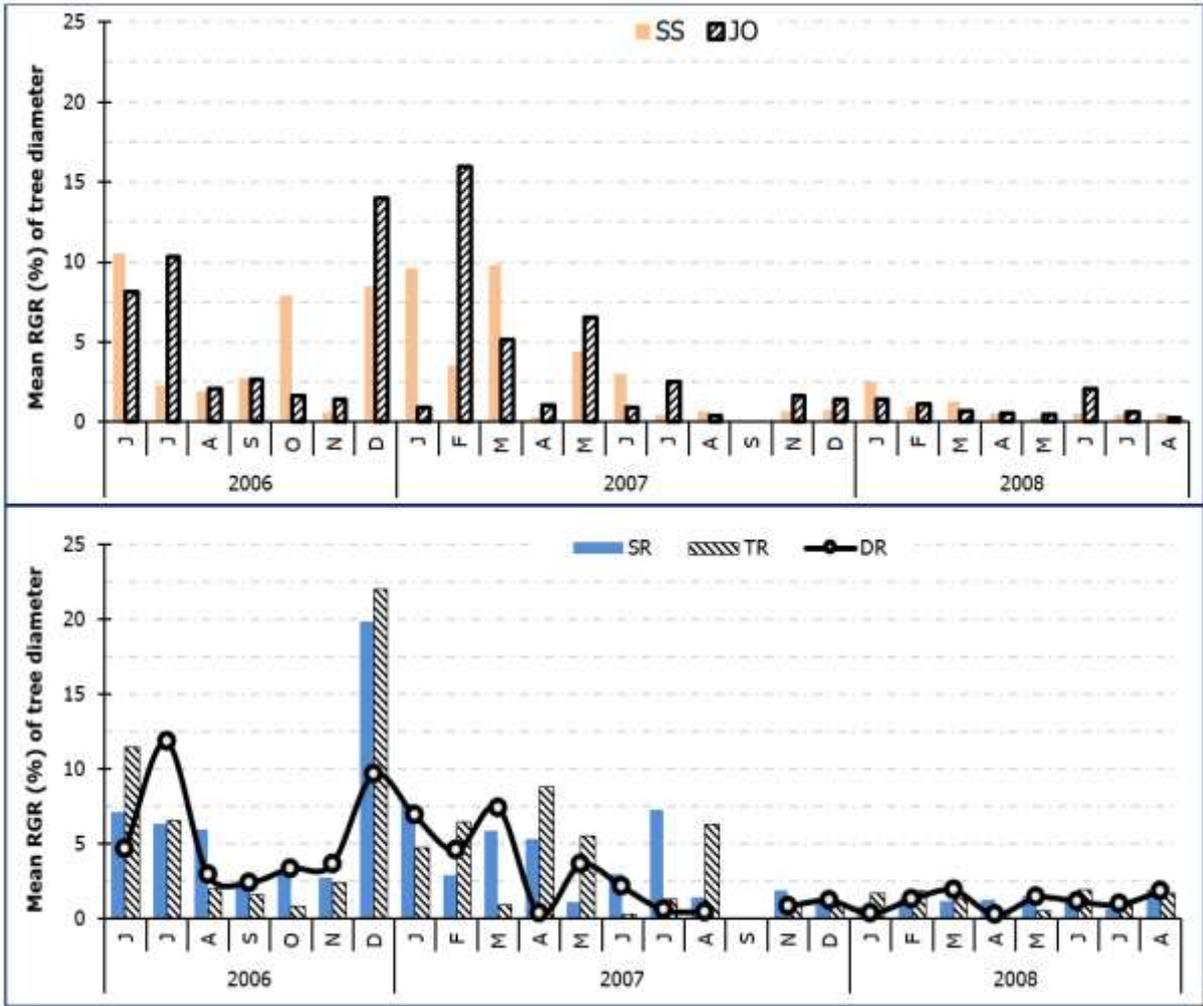


Figure 4 Mean stem diameter RGR (%) of *Jatropha* in JO, SS, SR, DR and TR

Tree-tree competition in T-G agroforestry increases total tree root density and reduces grass growth and T-G competition as tree density increases, although root biomass of individual trees is higher under low tree density than high tree density systems [28]. This could be the reason that TR (with higher tree density along the tree lines) had generally higher stem RGR (Figure 5) than the other competition treatments. Unlike agroforestry systems on deeper soil profiles where the depth of soil layers making the highest contribution to tree transpiration tends to increase with increasing tree density [29], tree productivity reductions in our study is expected to be considerably greater due to 0.6 m depth limit of the soil profile.

3.3.2 Treatment effects on post-pruning growth rate of trees

The absence of understory kikuyu and optimum tree spacing/arrangement in JO plots meant that there was no interspecific competition and minimum intraspecific competition. As a result, trees in the treatment acquired the highest height in just two months after pruning. Figure 5 shows that tree heights in all treatments increased towards the end of October, as soon as the leaves started to emerge. This, together with relatively high rainfall during November resulted in sharp tree height increases in the treatments. By March, tree height of all treatments started to level off due to low rainfall, late development stage and low temperature.

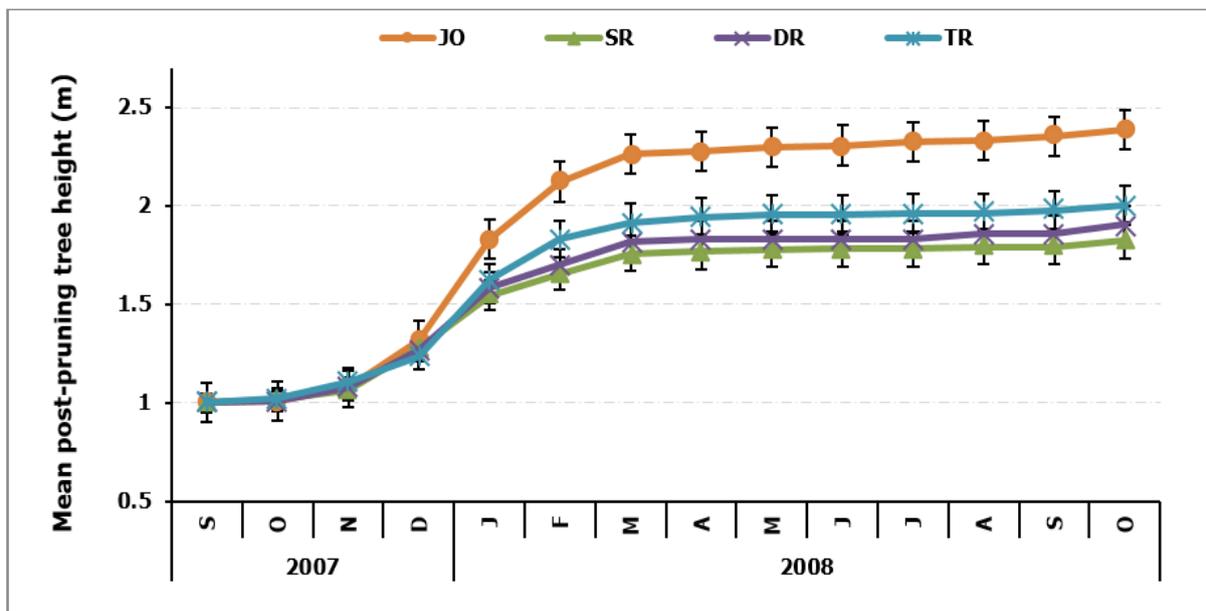


Figure 5 Tree height growth in JO, SR, DR and TR following tree pruning to one metre height

Across treatments, temporal increases in tree height following pruning were rapid. During the first two months, trees in all treatments were leafless. Starting from the third month after pruning (December 2007) and throughout the study period (till October 2008) trees of JO were the tallest, while SR had the shortest trees. Temporal patterns of height growth rates of all treatments were similar (Figure 6), with JO having maximum growth rate during November 2007 to March 2008. By October 2008, JO trees grew to a height of 2.4 m, which was 20 % more than the maximum tree height in the *Jatropha*-kikuyu treatments.

In high rainfall areas, *Jatropha* trees can reach a height of four metres within two to three years [30]. In the current study, prior to September 2007, maximum tree height observed in JO two years and seven months after establishment was 2.98 m. In the *Jatropha*-kikuyu treatments, peak tree height during that time was 2.03 m. These findings imply that even though there were high rainfall incidents during this period rainfall was not consistently high enough for maximum height growth of *Jatropha* trees to occur. Even when rainfall was high, height RGR was affected by BG interspecific competition.

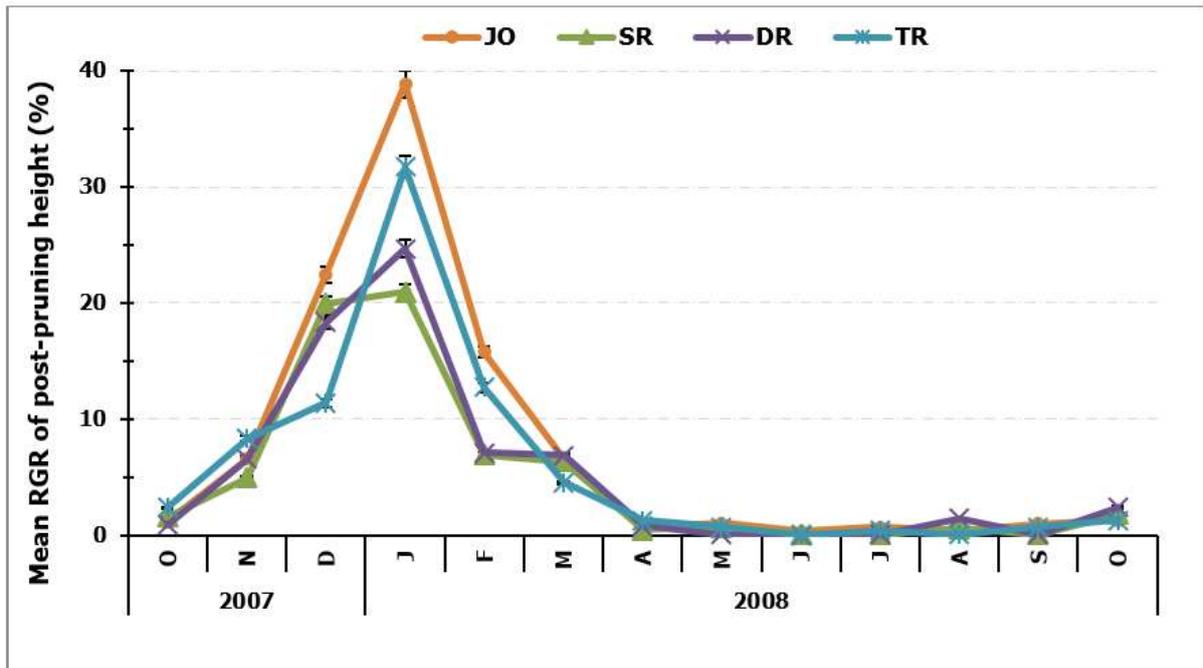


Figure 6 Relative growth rates (%) of tree height in JO, SR, DR and TR plots following pruning

Treatment ranking of height RGRs (Table 3) generally resembled the ranking of T-G interface to system area ratio (Table 1), which was JO > TR > DR > SR, especially during active growth months (October 2006 to April 2007). Trees of SR had the highest RGRs during kikuyu dormancy and lower rainfall and periods (Table 3). These lead to the following important findings:

- (a) Treatment responses to pruning were generally inversely related to the ratio of T-G interface to tree area. That is, the higher the ratio, the quicker the response and the better the performance during high rainfall period.

(b) Trees under high interspecific competition tended to make up for their slower response to pruning during reduced interspecific competition (May to July 2008) even when rainfall availability was low.

Table 3 Results of statistical analyses on tree height RGRs following top-pruning of the trees to one metre height in September 2007

Treatment	Nov/Dec 2007	Jan/Feb 2008	Mar/Apr 2008	May/Jun 2008	Jul/Aug 2008	Sep/Oct 2008
JO	26.21 ^a	15.86 ^a	1.53	1.27 ^a	2.56 ^a	2.20
SR	18.33 ^c	12.13 ^b	1.85	1.08 ^{ab}	1.76 ^{ab}	1.53
DR	19.65 ^c	13.93 ^b	1.26	0.49 ^c	1.12 ^b	1.65
TR	21.00 ^b	17.83 ^{ab}	1.34	0.77 ^{bc}	0.80 ^b	1.25
Significance	**	*	Ns	**	**	Ns
LSD _{0.05}	1.05	5.18	0.80	0.35	0.67	1.35
CV	2.48	15.48	26.60	19.41	22.01	36.72

(c) ^β Values followed by the same letter within a column are not significantly different

(d) * Significant at p = 0.01; ** Significant at p = 0.05; Ns = non-significant

Canopy pruning can enhance feasibility of *Jatropha* under agroforestry by ensuring temporal complementarity between *Jatropha* and companion species. As a case in point, limited irrigation was applied to groundnut intercropped between 3 m spaced and pruned *Jatropha* rows during a dry period and resulted in improved *Jatropha* growth by reducing weed competition [31].

3.3.3 Effects of treatments on seed yield

Jatropha trees can be expected to bear seeds in a year provided water availability is high [32] as confirmed in a one-year old irrigated *Jatropha* plantation (2 m-by-2 m layout) at a biofuel park in New Delhi that produced up to 0.43 kg of seeds per tree [33]. The first seed yield of the current study was due for harvest in March 2007; two years and three months after the trees were transplanted to the experimental site, signifying lack of consistently high rainfall.

Trees in JO produced the highest yield in all years (Figure 7). In 2007, the average seed yield was 95.2 g per tree, which was equivalent to 103.5 kg ha⁻¹. The yield in the *Jatropha*-kikuyu treatments ranged between 5.1 and 29 % of the control (JO) treatment. In 2008, the control trees yielded an average of 135.8 g tree⁻¹ (146.6 kg ha⁻¹), while trees in the combination treatments managed to produce only 5.1 - 17 % of that (7.4 - 25 kg ha⁻¹). Maximum yield (in JO) during 2009 increased to 351 g tree⁻¹ (381 kg ha⁻¹) as the trees were older than four

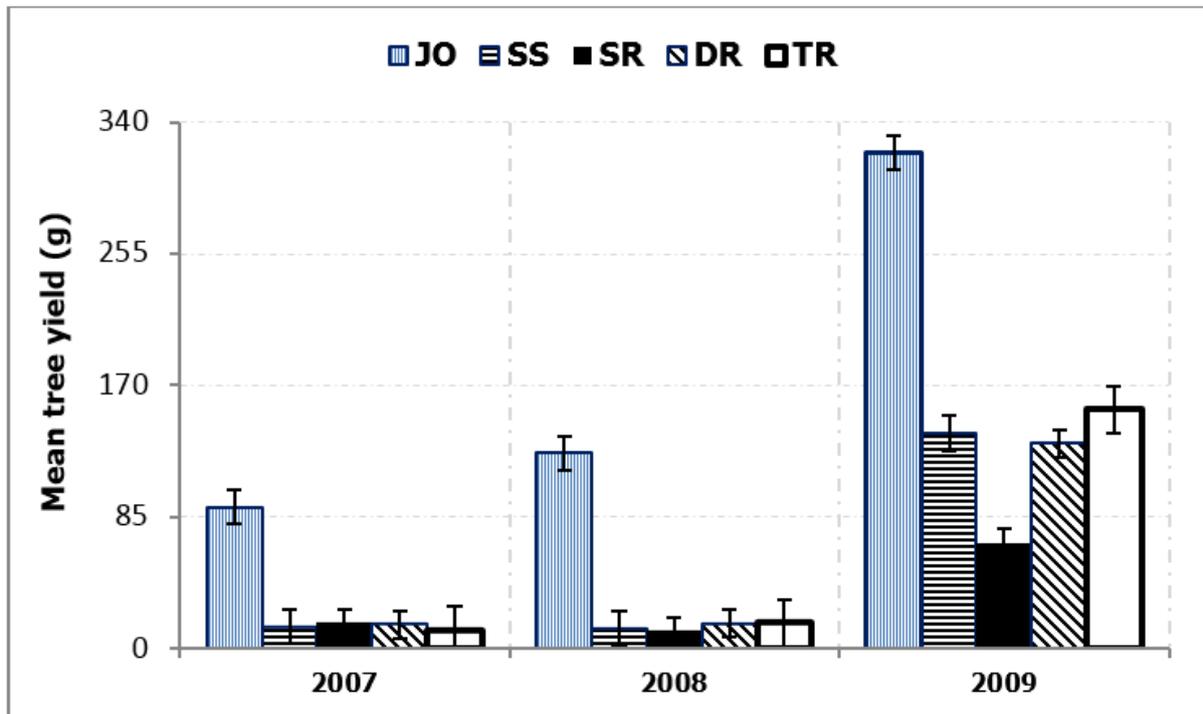


Figure 7 Mean tree seed yields (g) in JO, SS, SR, DR and TR plots

years and supposedly reaching the age of maximum yield. Trees of the *Jatropha-kikuyu* treatments showed more drastic yield increases (6 – 11 times) than JO trees (2.5 times). This showed that yield productivity in the mixed treatments was slower to peak.

Only in 2009 (third year of yield) did SR, DR, TR and SS show significant yield differences among themselves (Table 4). T-G interface length affected yield (Tables 3.1 and 3.4). JO trees had the shortest T-G interfaces and the highest yield. Trees of TR had the second highest yield because their (weighted) average length of the T-G interface (2 m) was shorter than those of SR, DR and SS. The differences in the lengths of T-G interface among SR, DR and SS did not lead to significant yield differences.

Table 4 Statistical results of tree yield (g) of the treatments during 2007 to 2009 seasons

Treatment	2007	2008	2009
JO	91.31 a ^β	126.20a	320.57a
SS	13.88 b	12.99b	139.00bc
SR	16.58 b	11.347b	67.99c
DR	15.56 b	16.27b	132.53bc
TR	11.81 b	16.51b	154.28b
Significance	**	**	**
LSD_{0.05}	10.59	9.15	72.02
CV	18.86	13.25	23.48

^β Values followed by the same letter within a column are not significantly different

* Significant at p = 0.01; ** Significant at p = 0.05; Ns = non-significant

Compared to reports of yields of up to 2 – 3 t ha⁻¹ in semi-arid areas [8, 33, 34], the current yields were extremely low. High values reported were most likely extrapolations of yields from single and mature trees with high yields [5]. On the other hand, during a 17-year period at Nashik in India mean seed yield of *Jatropha* was lower than 1.25 t ha⁻¹ [35]. Annual yields of 0.2 – 2 kg per tree have been reported [36] with yield variability of up to 0.85 kg per tree observed within the same plantation [37]. Trees of a five-year old rain-fed plantation on good soil produced 1.2 kg seeds per year, which was 40 % of yield under irrigation [38]. Hence, *Jatropha* trees can survive under stress but cannot be expected to have high yields [39]. Its productivity is high under sub-tropical conditions, while according to Köppen climate classification Ukulinga is temperate and warm with summer and winter rainfall. *Jatropha* is affected by even short-term water-logging [10], which occurred at the site intermittently.

Some methods of minimising effects of interspecific BG competition on productivity of *Jatropha* in agroforestry have been suggested, namely: clearing competing understory crops within 0.6 m distance from the trees [40], using spatial separation of resource use [42] and planting less competitive understory crops [17, 43].

3.3.4 Effects of treatments on harvest index

Harvest index of trees was determined to check if BG interspecific competition and tree spacing/arrangement in hedgerow intercropping affected vegetative tree growth more (or less) than tree yield. Figure 8 presents tree harvest index and outcomes of statistical comparisons among the treatments during 2007 and 2008. BG T-G

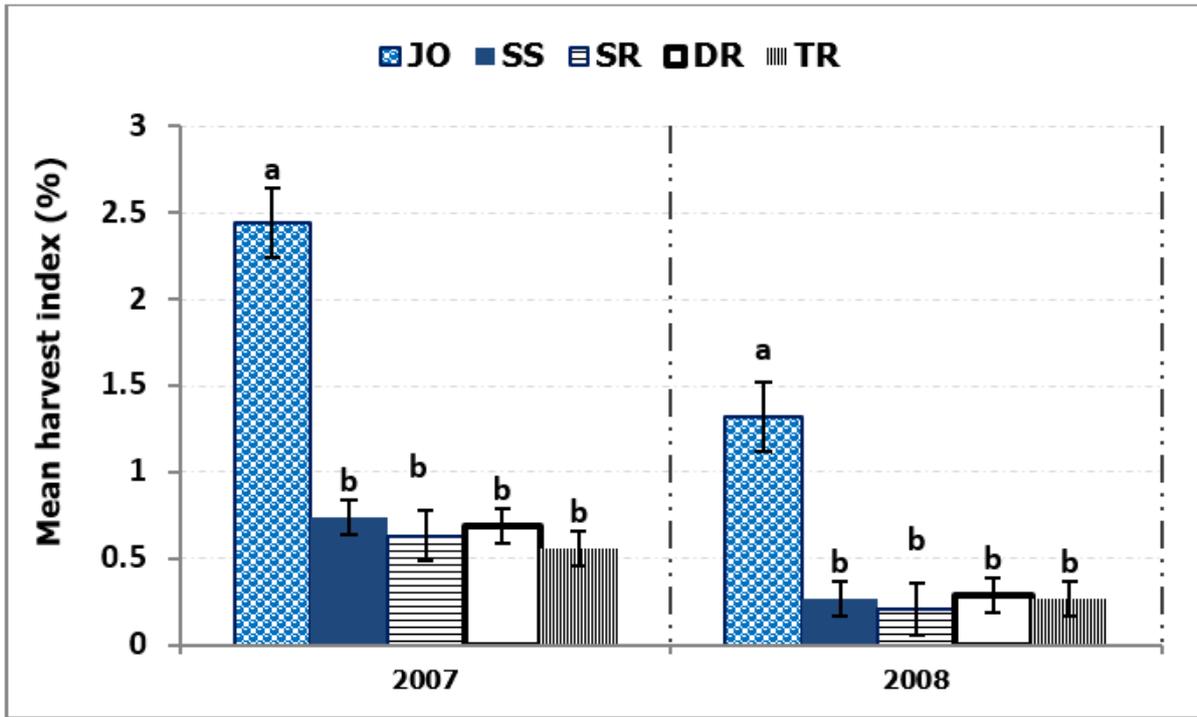


Figure 8 Analysis results on *Jatropha* harvest index of the treatments in 2007 and 2008

competition reduced tree harvest index, i.e. tree yield more than tree biomass. However, tree spacing/arrangement had no effect on harvest index implying that the treatments had proportional effects on tree yield and biomass. In contrast, [31] recommended wider spacing in semi-arid regions as narrower layouts lead to sooner canopy closure and lower yield to biomass ratio in mature plantations.

In 2007 and 2008, SR, DR, TR and SS did not have significant differences in yield or stem diameter. This resulted in linear and positive correlation, with high coefficient of determination (0.89 in 2007 and 0.88 in 2008), between stem diameter and yield (Figure 9). Similar correlations between basal stem diameter and seed biomass have been found in other species [41]. It should be borne in mind, however, that there is no linear relationship between diameter of a tree and its yields across years. The reason is that young *Jatropha* trees increase in stem diameter from year to year while their yields may fluctuate between an increase and a decrease in successive years.

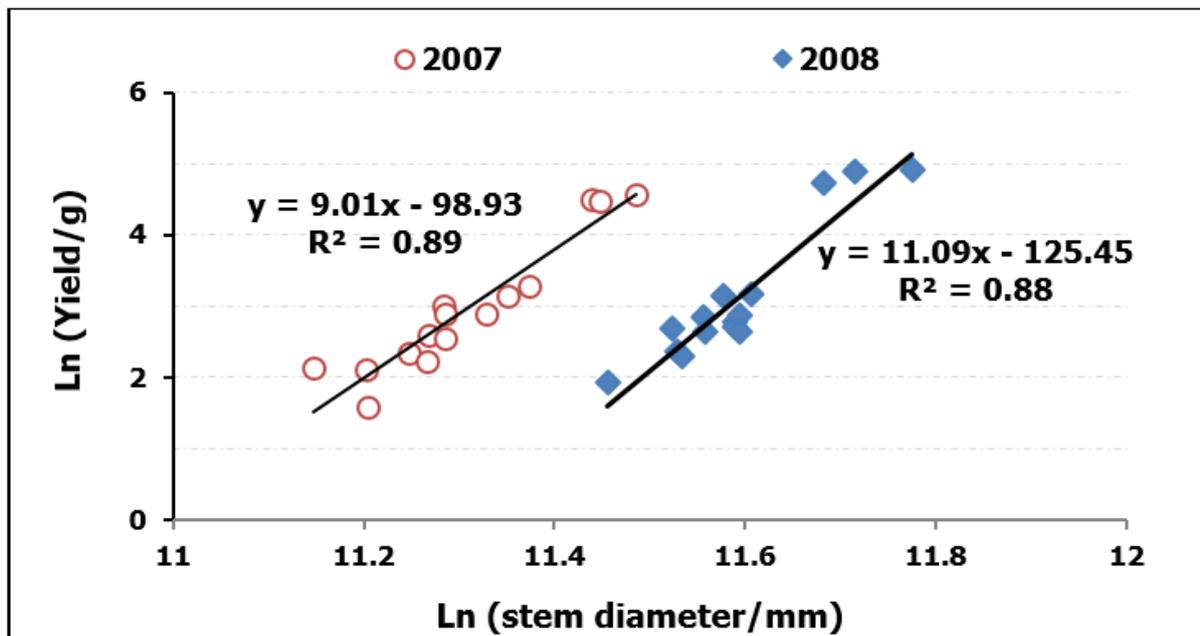


Figure 9 Yield per tree vs. mean stem diameter using pooled data for 2007 and 2008 seasons

3.4 CONCLUSIONS

Jatropha yield and growth was reduced by interspecies BG interactions leading to the acceptance of the hypothesis that the interactions were competitive. The fact that none of the spacing/arrangement treatments had significantly and consistently the highest productivity led to the rejection of the hypothesis that BG competition and productivity reductions of *Jatropha* can be minimised by manipulating tree arrangement/spacing without changing tree density.

Water availability accounted for the differences in productivity performance among treatments. When high water availability and kikuyu dormancy coincided, there was no significant difference in tree RGR among treatments. Post-pruning height RGR was affected by BG interspecific competition and tree spacing/arrangement even when rainfall was high. High T-G interfaces resulted in slow initial tree response to pruning followed by compensatory growth during reduced interspecific competition periods even when water availability was low. Tree yield was generally inversely related to T-G interface length especially as trees matured toward their maximum-yield age. Yield reduction due to BG interspecific competition was greater than biomass reduction, while tree spacing/arrangement affected yield and biomass proportionally.

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