YEILD, PHOTOSYNTHESIS, LEAF AREA INDEX, AND LIGHT REGIMES OF CORN AND SOYBEANS GROWN IN VARIOUS POLYCULTURE CROPPING SYSTEMS

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ABSTRACT

YIELD, PHOTOSYNTHESIS, LEAF AREA INDEX, AND LIGHT REGIMES OF CORN AND SOYBEANS GROWN IN VARIOUS POLYCULTURE CROPPING SYSTEMS

By

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Grain yields, Land Equivalent Ratio (LER), Leaf Area Index (LAI) and Apparent Photosynthesis (AP) of eighteen corn and soybean polyculture cropping systems were evaluated.

The occurrence of comparatively large LAI's and large AP rates for corn and soybeans correspond to significant increases in the grain yield of both crops. LER's of 1.10 or greater were achieved only when one crop had a competitive advantage due to either crop density or spatial intimacy between the two crops. High corn populations and/or the least intimate corn/soybean spatial arrangement favored the development and yield of corn, while the closest spatial intimacy favored soybean development and yield.

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INTRODUCTION

Research and development of mixed cropping systems should benefit the agricultural technologies of both "developing" and "developed" nations of the world. The extensive use of mixed cropping in developing nations has often connoted a backward or simplistic farming method, and assumedly for that reason, one which is not applicable to developed western agriculture. There are, however, some appealing ecological and economic aspects of mixed cropping which could make a significant contribution to an agricultural technology evolving within the constraints of a limited petroleum supply and the growing awareness of the fragility of nature.

Mixed cropping is most often associated with subsistence farming, and within this context lies the importance and relevance of mixed cropping to future U.S. agricultural technology. The subsistence farmer must derive the bulk of his sustenance through a farming technology which is low in capital inputs (fertilizer, herbicides, etc.), yet high in ecological stability. He is substituting the cheap and abundant ecological inputs for the scarce capital inputs. In this way the perilous effects of insects, disease, and climatic vicissitudes are considered before the fact, by exploiting ecologically stable cropping systems, rather than after the fact, by applying antidotal chemical controls to ecologically instable cropping systems.

U.S. agricultural technology in recent years has begun to acknowledge and address the deleterious effects of some of its agricultural production techniques. Further, the cost of petroleum and petroleum derived production inputs will remain volatile as the spector of petroleum shortages becomes more real. It would therefore be prudent to begin developing technologies which require less energy in the form of fertilizer, herbicides and field operations. Agricultural technologies should be developed which employ the natural stability and competitiveness of a diverse ecosystem which insulates against the effects of disease, insects, unwanted plants, and variable rainfall. The subsistence farming systems, with their emphasis upon mixed cropping, offer a research framework from which an ecologically and economically responsible crop production system may be developed.

LITERATURE REVIEW

Mixed cropping, polycultures, associated cultures, and intercropping have all been used to describe agricultural systems in which two or more crops are grown together in the same field at the same time. These systems have been used throughout history in many parts of the world (8, 18).

In the early part of this century American agriculture used intercropped soybeans and corn as a method of forage production, or grain production (9). More recently, Wahua (43), Alexander et al. (3), Pendleton et al. (32), and Crookston et al. (9) have examined the multiple cropping system under intensive agriculture conditions. Developing nations, where multiple cropping is most prevalent, have begun research to identify the merits of multiple cropping (10, 12, 39, 24, 1, 19).

The merits of multiple cropping must largely respond to the needs of a particular agricultural and sociological setting. In the U.S. this would mean increased production per unit area, whereas in developing nations it would encompass not only yield per unit area, but also economic return, nutrition, and risk reduction.

Evaluation of the multiple cropping system can be based upon several parameters: dry matter production, protein content of grain, economic return, or grain yield (25, 21). All are relevant depending upon the objectives of the experiment. Different methods have been employed to compare multiple cropping grain yields and yields of monocropping. Kass (25) has reviewed several methods. Relative Yield Total (RYT) and Land Equivalent Ratio (LER) have received the most attention in the literature, with LER probably used more often. The apparent advantage of LER is it's applicability to experiments which alter plant densities, while RYT can only be used under constant densities. LER and RYT are exactly the same when using constant populations. Both are relatively easy to calculate and reflect the performance of multiple cropping relative to moncultures. LER is calculated in the following manner:

$$\text{LER} = \frac{\text{Yield of crop A in polyculture}}{\text{Yield of crop A in monoculture}} + \frac{\text{Yield of crop B in polyculture}}{\text{Yield of crop B in monoculture}}$$

LER's greater than 1 indicate a yield advantage by growing crops together on the same unit of land versus growing crops separately with each crop occupying one-half the polyculture unit area. For instance, using data from Crookston (9), corn and soybeans in polyculture yielded 50 and 10.5 quintals per hectare, and monoculture corn and soybeans yielded 79 and 27 quintals per hectare, respectively. Using the LER formula:

$$\frac{50}{79} + \frac{10.5}{27} = 1.02 \text{ LER}$$

This means that corn and soybeans grown in polyculture yielded only slightly better than if each drop had been grown in monocultures.

Multiple cropping studies can be considered competition studies, since in most cases where multiple cropping is successful, competition for growth factors occurs (23, 19, 11). Competition exists between plants of different species (inter-specific competition) and among plants of the same species (intra-specific competition). The more aggressive plants in a polyculture, those of the dominant crop, will compete more favorably and gain a greater share of the growth factors (40). In other words, the inter-specific competition favors the dominant crop. Since the densities of the dominant crops in polycultures are usually between 50-70% of their monoculture densities, corn intra-specific competition is reduced. Therefore, the ultimate benefit of the polyculture system depends, in large part, upon how well the dominant crop self-compensates (6), that is, how well it can yield when intra-specific competition is reduced. The dominated component of the polycultures will yield less than it's monoculture counterpart, and the magnitude of the yield reduction will be determined by the availability of growth factors, as defined by the dominant crop, and by how well the dominated species utilizes the available growth factors. Generally, at populations found in polycultures, inter-specific competition is greater than intra-specific competition (6). The acquisition of growth factors and ultimate yield are determined by both inter- and intra-specific competition.

Factors which affect the performance of multiple cropping systems are the same as those affecting a monoculture system, but the interaction of the different species has led researchers to examine them in greater detail.

Because of the complexities of mixed cropping systems, few experiments have been done which sought to analyze the effects of water competition or temperature changes in polyculture systems. Fisher (17, 14) reports that during the short-rains in the Kenyan highlands, water competition between interplanted corn and beans reduced the yield of both, relative to monoculture. This observation, determined from a spacing study, was faciliated by lower than average rainfall during his study. Temperature effects on soybeans reported by Wahua (42) were observed in a shading experiment. He concluded that shading reduced the canopy temperature, thus reducing energy losses via respiration and transpiration, allowing energy to be used for fixation of atmospheric nitrogen.

The nutrient and fertility aspects of multiple cropping have received much more attention than have water and temperature. It is reported that polycultures exploit soil nutrients better than monocultures due to their different root systems, nutrient uptake period, or interaction between legumes and non-legumes. Enyi (12) reports that cereals and legumes usually have major nutrient absorption during the grain filling period. If this period can be altered so that filling of the different species occurs at different times, then the polycultures system will exploit more soil nutrients in a given season. This has been reported as a possible reason for observed LER's greater than 1 when corn and pigeon peas were intercropped (10). Soybeans take up 80% of their nutrients from beginning growth to physiological maturity (35). This could explain the greater interspecies competition when corn and soybeans are planted at the same time, since their grain filling periods coincide (35). Agboola contends that there is probably little competition for immobile nutrients, but that this is probably not the case for mobile nutrients like nitrogen (1). Some fertility studies have shown that polycultures respond much less to fertilizer application than do monocultures

(16, 17, 1). However, Hart (22) reported, from bean (*Phaseolus vulgaris*) and corn (*Zea mays L.*) polyculture studies done in Central America, that fertilizer application does affect the polyculture system. Under no fertilizer application there was no significant difference between monoculture and polyculture bean yields, but with fertilizer application polyculture bean yields were significantly lower than for those grown in monoculture. Polyculture corn yields were significantly lower than monoculture under no fertilizer treatment, but were not significantly different when fertilizer was applied.

The interaction of the component crops' systems has been the topic of several studies. Soil microorganisms are influenced by multiple cropping systems (35). C. L. Keswani et al. (26) found that bacterial populations increases appreciably when intercropping corn and soybeans, but that fungal populations decreased. Fungal population around the soybean roots were affected much more than around the corn roots. No effects of the microorganism on yield were noted, but it was reported that some bacteria produce growth stimulation substances.

A much larger debate surrounds the benefits of cropping non-legumes with legumes. It is usually reported that nitrogen fixation by legumes is reduced when they are intercropped or if the legume is deprived of light (49, 43, 42). However, Wahua found that when soybeans were intercropped with dwarf sorghum, N_2-fixation activity by the soybeans was increased by 264% (43). He offered three possible explanations for these results: (1) "allelochemical" effects between the sorghum and soybeans, (2) sorghum roots reduced nitrate concentration around soybean roots, and (3) "staking effect" where sorghum plants physically supported the soybeans thus allowing greater light penetration into the soybean canopy. It is reported that some legumes can fix nitrogen better than others, and that some legumes can excrete nitrogen from their roots to the other plants within close proximity (2). Agboola (2) ranked three legumes according to their N_2-fixation ability. He ranked calopa (Calopogonium mucunoides) better than cowpeas (Vigna sinensis) and greengrams (Phaseolus aureus), and cowpeas better than greengrams. Of these three legumes, greengrams excreted the most nitrogen. Greengrams excreted the equivalent of 31.3 Kg/ha which could be used by corn intercropped with it. This differential ability to excrete nitrogen has been shown to cause different yield responses when these legumes were intercropped with corn. Under no nitrogen application the yield of corn was significantly higher when intercropped with greengrams versus monoculture corn or corn intercropped with either cowpeas or calopa. This suggests that there could be fertility benefits to non-legumes when intercropped with legumes, and that the benefits will vary with a particular legume.

Light has received the greatest attention and has been cited most often as the factor influencing yield of polycultures (18, 10, 37, 43, 1, 47). Pendleton suggests that better light utilization caused corn yield increases when intercropped with soybeans. In his study, four rows of corn were alternated with four rows of soybeans. The yield of the interior rows of intercropped corn exceeded that of monoculture corn. But the increase of corn was off-set by an equal reduction in soybean yields (32). Another study by Altieri et al. (4) reported that light interception was increased 19.3% at the vertical mid-point of a corn-bean polyculture. As mentioned in the Pendleton study, soybean yields were depressed, this being attributed to reduced light intensities in the canopy. Wahua (35) and others (42, 32) reported a 30-60% reduction of incident irradition at the top of intercropped soybeans canopies, depending upon the intensity of the association. Even with the observed absorption increases of the corn canopy, there do not appear to be any differences in total absorption between the canopies of polycultures or monocultures (46).

Associating different crops together in one unit area more closely resembles a natural ecosystem, which is characterized by greater organismal balance and stability. It is not surprising, then, to find reports of reduced incidence of insects and diseases with polycultures. Although few studies have specificly examined the incidence of disease, there are reports that disease is reduced in multiple cropping systems (46, 24). Insects were specificly studied by Altieri et al. (4). When corn and beans (Phaseolus vulgaris) were planted at different times, he found that the incidence of leaf-hopper damage of beans was reduced when corn was planted 20-30 days before the beans, and the incidence of Fall armyworn (Spodoptera frugiperda) damage of corn was reduced 88% if beans were planted 20-40 days before corn. Willey has reported similar results (46, 24).

Weeds can be considered as part of the ecosystem competing for the various growth factors. Due to interplant competition, especially with the high plant populations found in polycultures, weeds or undesirable plants would be expected to be less of a problem in polycultures than in monocultures. This appears to be true, as several researchers have reported reduced incidence of weeds in polycultures (6, 46). One study (22) reported that weeding had little effect on polyculture bean yields. Weeding generally increased the monoculture corn yields, but had little effect on polyculture corn yields.

In pursuit of increased grain yields, researchers have altered the micro-climatic environment of polycultures, such that maximum exploitation of growth factors can be realized by the polyculture crop components. This is most effectively done by changing the relative plant densities, altering the spatial arrangement of the crops, or exploiting phenological differences between crops. Indeed, the bulk of multiple cropping experiments have concentrated on these parameters. It is helpful to distinguish species response to each of these factors, since the dominant or taller crop will be affected differently than the shorter, dominated crop. The literature abounds in the specific performance of corn, sorghum, manioc, soybeans, dry beans, groundnuts, et cetera. It is, however, of greater analytical benefit to divide the polyculture crops into two distinct groups under a general heading of the dominant and dominated components. In this manner some general conclusions can be reached concerning component response to the environment.

Considerable research has been conducted concerning the plant population of the dominant component of polycultures. Freyman (20) stressed the importance of plant population in polycultures. Osiru (31) and others (47, 6, 23) pointed out that the benefits to polycultures when population of the dominant crop exceed 50% of optimum monoculture densities. Pendleton (32) reported that yield increases occurred when intercropped corn rows were reduced from 100 cm to 60 cm, effectively increasing the plant population of corn. Wahua (44) reported that sorghum yields increased as its population increased in the polyculture. This same trend has been cited by other researchers (9, 25).

The dominated components of polycultures systems were always adversely affected by population increases of the dominant component (44). Their yields were always reduced (9, 10), except when there is height parity or when their populations exceed those of the other component (44, 17).

The dominant component will be less affected by altering the spatial arrangement than by changes in populations. If the dominant component was at optimum populations, most researchers reported little benefit from altering spatial arrangement (9, 24, 18, 1, 15). However, some have reported a positive yield advantage when altering spatial arrangement (19, 15). Freyman (20) reported that the yield of the dominated crop within the polyculture system can be positively influenced by spatial arrangement, but Francis (18), Evan (13) and Fisher (16) reported that spatial arrangement had no effect on yield.

Morphological changes of the dominant crop occur when altering either the population or spatial pattern of the polycultures. Francis (19) and Enyi (12) reported that corn height was reduced by competition. In the same study Francis reported morphological changes of corn due to intra-specific competition, with the most pronounced effect being that on ear weight. Leaf area indices (LAI) were reduced in cereals, beans and cowpeas (12), while in other polycultures, LAI's were slightly increased (46). Dry matter yields were increased in corn when intercropped with greengrams (2), and yields increased when sorghum was intercropped with pigeon peas (46). As population increases, the yield per-plant generally decreases (15, 47). In polycultures, the yield per-plant is generally higher than in monocultures at similar populations (31).

The morphological changes of the dominated component are very much in accordance with those expected in a reduced light environment. The number of branches per plant, number of flowers set, number of pods per plant, and dry weight for polyculture legumes are all reduced. Legumes fix less nitrogen (2), but there appears to be differential ability of legumes to fix nitrogen under the same shading conditions (1).

Effectively using temporal differences is the best method for realizing benefits of polycultures (16, 33). Willey (46) contends that temporal differences more effectively exploit the environment. Two experiments, one with a bean/corn polyculture and the other with either castor-bean/soybean or castor-bean/groundnuts polycultures, illustrate the influence of planting date on yield of component crops. When beans (Phaseolus vulgaris L.) were planted before corn (Zea mays L.), they did not affect the corn yield, but bean yields were greater than if planted simultaneously with corn. In polyculture with castor-bean, the dominant crop, soybean and groundnut yields were greatest when they were planted before castor-bean. Castor-bean yields were only slightly reduced when simultaneously planted with either soybeans or groundnuts.

To achieve maximum grain productivity, this body of literature suggests:

1. The dominant species of the polycultures must be planted at densities greater than 50% of their optimum monoculture densities.

2. The dominant species is less affected by the spatial arrangement than the dominated species. Therefore, dominant crop spatial arrangement should be altered to produce the optimum environment for the dominant crop.

3. Whenever possible, temporal differences in grain fill period

must be exploited, either through the use of shorter maturity crops or by different planting dates.

4. Since species are differentially affected by competition, species should be compatibly matched to reduce inter-specific competition.

5. Inter-specific competition for nutrients is low, and in some cases mutual cooperation seems possible.

OBJECTIVES AND HYPOTHESIS

The major thrust of this experiment was to determine the relationship between cropping system productivity and plant competition. The specific objectives were:

1. To evaluate the relative grain productivity of certain monoculture and polyculture cropping systems.

2. To determine if polyculture grain productivity was influenced by corn row width.

3. To determine the influence of soybean spatial arrangement on polyculture system grain productivity.

All of these objectives dealt with the influence of inter-specific and intra-specific competition on system productivity.

The first and second objectives sought to validate or invalidate my hypothesis that high degrees of intra-specific competition cause inefficient exploitation and use of available growth factors. This hypothesis was based upon monoculture corn density studies by Williams et al. (48) and Whitaker (45) which sought to determine the optimum yield density (density at which maximum corn yield occurs). Plant populations greater than this density produced less grain. According to Stringfield (39), this decrease in grain production stemmed from the high degree of competition for available resources, that is, water, light, and nutrients. The effects of competition at densities beyond the yield threshold density are quite obvious, but subtler effects begin at lower densities. It can be shown that the negative effects of competition begin at densities much lower than the yield threshold density.

The relationship between maximum yield and competition in ecological settings is somewhat analogous to the relationship between maximum production and cost in an industrial setting. Industry rarely produces at the theorical maximum because, at the theorical maximum, the additional costs of production exceed the additional worth of the product. This concept is, of course, the "Law of Diminishing Returns" and is graphically represented by a production function (Figure 1). The point at which each additional unit of cost produces an equal amount of additional output is the point of greatest efficiency. This production function concept can illustrate that the negative effects of competition begin at densities much lower than the threshold density and that the high degree of intra-specific competition causes the system to operate at low levels of efficiency.

The graphic representation of a production function requires several factors--total production (total yield), units of inputs (plants per hectare), marginal returns (the difference in total yield between units of input), and marginal costs (the difference in total cost between units of input). At the plant density where marginal cost equal marginal returns, plant production is at the most efficient point. The total production curve reflects the customary yield decrease as corn population increases past a critical density. The differences in total yield between each population, the marginal returns, were determined and plotted on the same graph. The cost of production at each density was somewhat more difficult to derive than

the other parameters. Whitaker et al. (45) have shown that as corn plant density increases, the yield per-plant decreases. The inverse relationship between population and yield per-plant was assumed to be an accurate reflection of the level of intra-specific corn competition for growth factors. As the population increased, a certain portion of the per-plant yield was lost due to the effects of competition. Therefore, it was assumed that the cost incurred by the system was in the loss of per-plant productivity. Greatest efficiency would be realized when the loss of per-plant productivity equalled the marginal returns.

To determine the production cost, I assumed that each variety had a genetic maximum per-plant potential, when grown without competition from other plants. Stringfield (39) reported that per-plant corn yields started to linearly decrease after a population of 5,000 to 7,400 plants per hectare was achieved, therefore the genetic maximum yield per-plant value was determined by extrapolation to plant densities of 5,000 plants per hectare. Figure 1 and 2 show the results of these calculations for two different corn varieties.

The intersection of the marginal cost and marginal returns lines shows the density at which the loss of per-plant productivity equalled the amount actually produced by the plant. The point of maximum per-plant efficiency occurred at plant densities below the density of maximum yield per unit area. A greater portion of the per-plant potential was sacrificed for competition than was realized in grain production. The growth factors exploited by each corn plant in monoculture beyond the most efficient plant densities were not efficiently converted into grain yield. The first objective sought to determine

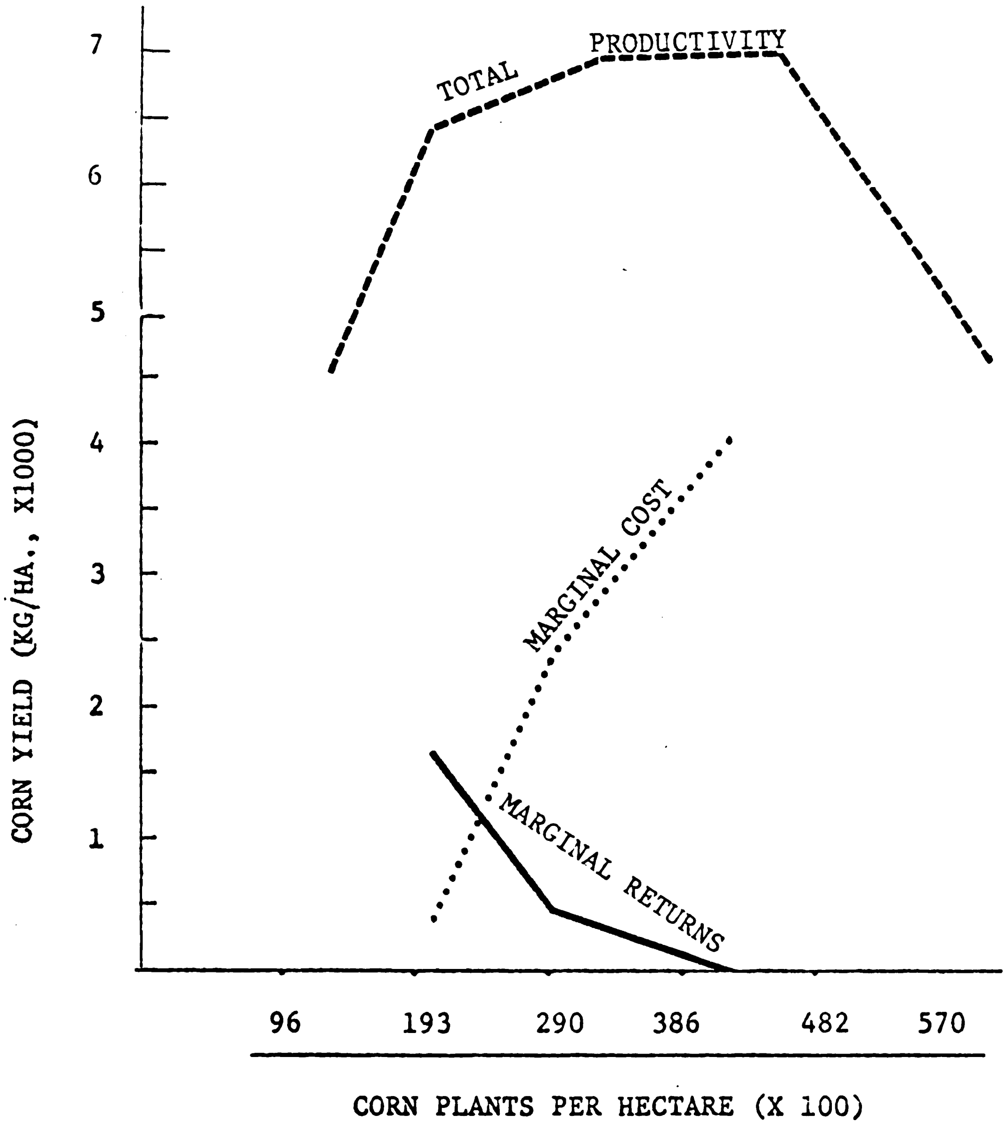

FIGURE 1. The analysis of the yield of corn in a production function format. (Data from, W. A. Williams et al., Crop Sci. 8:303-308; 1968.)

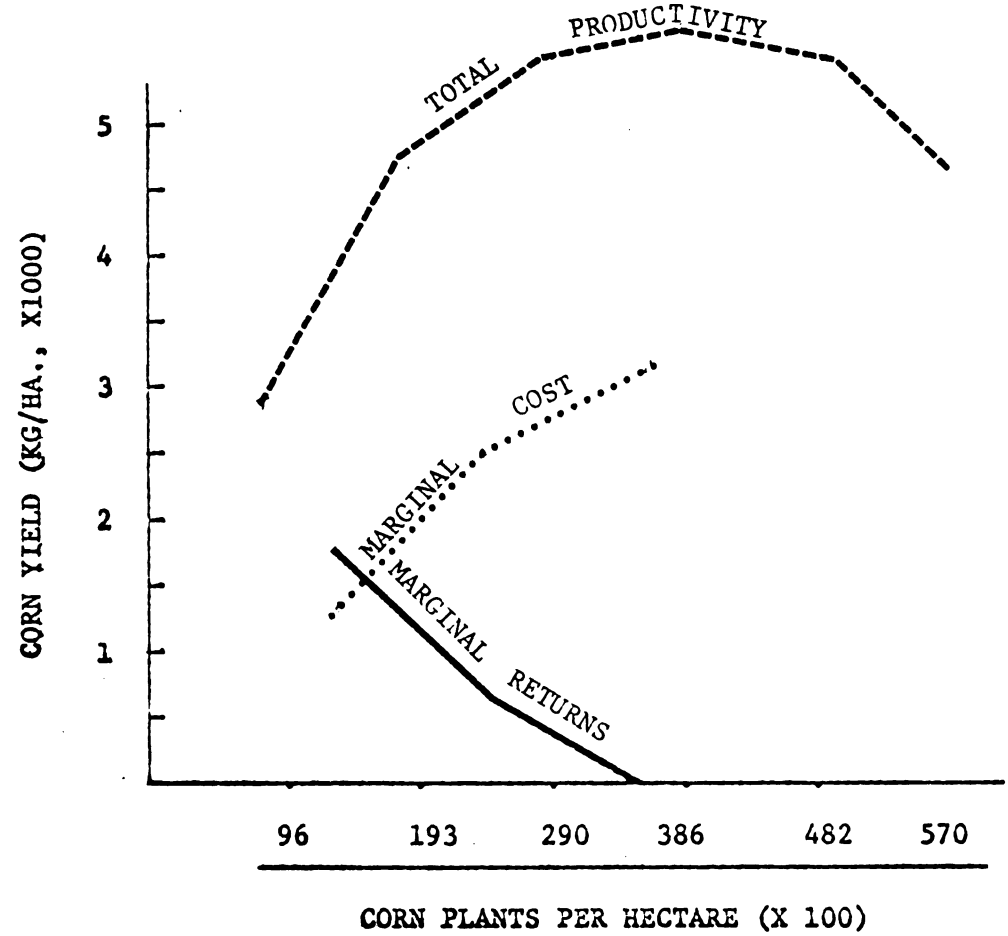

FIGURE 2. The analysis of the yield of corn in a production function format. (Data from, G. H. Duncan, et al., 1958, Adv. Agron.)

whether the replacement of corn plants, beyond the most efficient density, by soybean plants would foster greater efficiency in the utilization of the available growth factors, and thus achieve higher productivity from the total cropping system.

The first objective sought to determine the relative yield difference between monoculture and polyculture systems for certain crops; the second objective sought to evaluate the relative yield difference within polyculture systems. Consonant with the hypothesis' emphasis upon the relationship between intra-specific competition and system productivity, the second objective recognized the differential degrees of intra-specific corn competition associated with different corn row widths. Data from the Missouri Agricultural Experiment Station served as an excellent illustration of within-row spacing alteration for corn and its effects of yield per-plant (45). In this experiment each of five corn plant populations was planted in 20", 25", 30", 35", and 40" row widths. The proximity of corn plants within the row influenced the per-plant yield; yield per-plant increased as within-row spacing increased. This suggested that intra-specific competition increased as row width became wider. Objective two sought to determine the response of polyculture productivity to subtle changes in the level of intra-specific competition of corn.

Although objectives one and two both dealt with intra-specific competition, objective one dealt with the "macro" affects (at the population level), whereas objective two dealt with the "micro" affects (at the plant spacing level).

The third objective, to determine the influence of soybean spatial arrangement on polyculture system productivity, dealt with polyculture system productivity as it was influenced by the relationship between the soybean/corn inter-specific competition and the corn intra-specific. This objective recognized the intrinsic relationship between the level of system inter-specific competition and component crop intra-specific competition.

Intra-specific competition was minimal when the intimacy between plants was least, however, as the intimacy between corn plants decreased, the intimacy between corn and soybean plants increased. For instance, in the 75 cm row width the corn plants were less intimately associated with each other than in the 100 cm row width, but the corn plants in the 75 cm row width were much more intimately associated with the soybeans than in the 100 cm row width. Based on my hypothesis that high levels of intra-specific competition are responsible for inefficient utilization of the available growth factors, maximum efficiency and highest productivity should have occurred when intra-specific competition in both crops was lowest.

This clearly suggests that polycultures are faced with a "no-win" situation due to the intrinsic relationship just outlined. Therefore, it was assumed that intra-specific competition between plants of the taller corn would dictate system productivity. Objective three sought to determine whether intra-specific corn competition or intra-specific soybean competition had a greater impact on polyculture system productivity.

MATERIAL AND METHODS

An experiment involving mixed cropping was conducted at the Michigan State University Crop Science Research Farm in E. Lansing, Michigan during the 1978 growing season.

The soil was classified as a Conover loam (0-2%, fine-loamy, mixed, mesic, Udollic Ochraqualfs). The previous crop, Mammoth clover (Trifolium pratense L.) was plowed down on May 19, 1978 and the soil was disced three times before planting. A complete fertilizer, 19-19-19, was broadcast applied at a rate of 64 Kg of N-P_2O_5-K_2O per hectare on May 25, 1978 and incorporated into the soil. The field was culti-packed once just prior to planting. Lasso herbicide (a.i. alachor) was applied at a rate of 1.96 Kg/ha one day after the crops were planted.

A maturity group II soybean (Glysine max., L. Merrill, var. Cole) and a short seasoned corn hybrid (Zea mays, Michigan Hybrid 5802) were hand planted on June 1 and May 29, respectively, in a 2 x 3 x 3 factorially arranged randomized complete block with four replications. The eighteen treatments, planted in 3 x 4 meter plots, consisted of two corn densities, three corn row widths, and three soybean spatial arrangements. Monoculture corn, at both high and low populations, and soybeans were included in each block.

The two corn densities, a low population of 22,500 plants/hectare and a high population of 45,000 plants/hectare, were planted in three row widths. In the first and second row widths, single corn rows were spaced 75 cm and 100 cm apart, respectively. In the third corn row width paired rows of corn were spaced 130 cm apart; the rows within pairs were separated by a distance of 40 cm.

The soybean plant population remained constant at 300,000 plants per hectare as the soybean spatial arrangement was altered. The three soybean spatial arrangements represented three levels of spatial intimacy between the corn and soybean rows (Figure 3). The distance between corn and soybean rows was 17, 25, and 38 cm in the 75 row width and 25, 38, and 50 cm in the 100 and 130 cm row widths. In each row width, the smallest distance between corn and soybeans represented spatial level one; the next closest distance, level two; and the greatest distance, level three. Spatial levels one and two had two rows of soybean between the rows of corn, which required seeding rates of 11.25 and 14 seeds/meter of row in the 75 and 100 cm row widths, respectively. In the third spatial level of the 75 and 100 cm row widths, one row of soybeans alternated with one row of corn. The soybean seeding densities in the third spatial level were 22.5 and 30 seeds/meter of row. In the 130 cm corn row width, a constant soybean seeding rate of 22.5 seeds/meter of row was used in all three spatial levels.

At harvest, the final corn and soybean stand densities plus lodging scores were recorded. These densities were used whenever plant data were reported.

All the data reported in this experiment were analyzed in accordance with the multi-variant statistical design, except monoculture and polyculture productivity comparisons, which were examined by a one-way analysis of variance.

Plant husbandry during the course of the growing season consisted

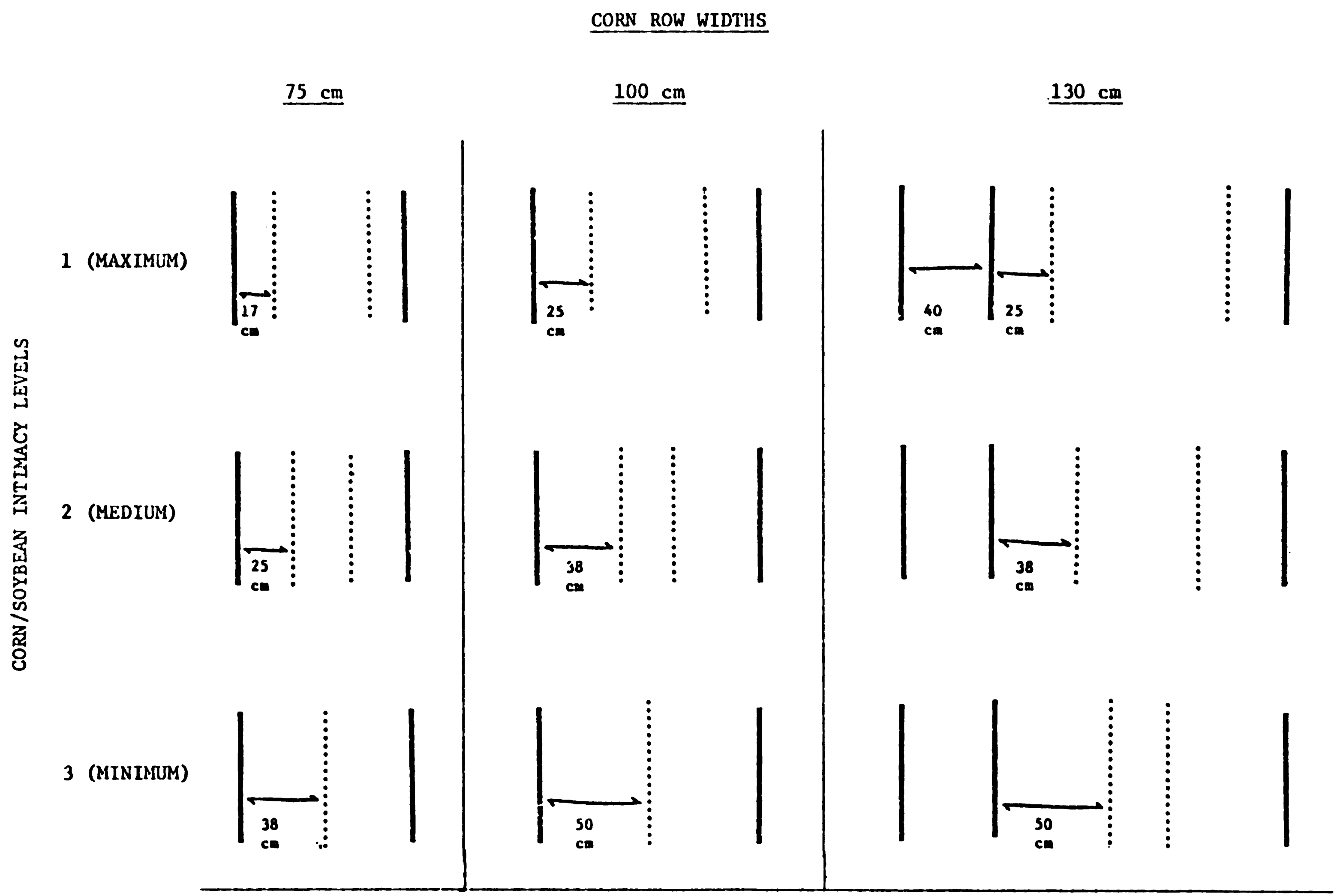

FIGURE 3. Schematic diagram of the various arrangements of corn and soybean rows for the polyculture cropping systems. Solid and dotted lines represent corn and soybean rows, respectively.

weeding and incidental control of insects. The plots were clean weeded five weeks after emergence and were kept essentially weed free during the course of the experiment. One plot was sprayed with Sevin (Carbaryl) to control Mexican Bean Beetle (*Epilachna varivestis*); damage was minimal and border rows were the only affected portions of that plot.

Rainfall during the course of the experiment was slightly less than average but was generally adequate and timely. Corn plants showed the typical rolled leaves symptoms of water stress only one afternoon throughout the growing season. The seasonal distribution of rainfall can be seen on Table 1 in the Appendix.

Components of yield were recorded for soybean and corn. Soybean yield components for each treatment were determined from six mature plants, two plants from each of three replications, taken prior to harvest. The characteristics measured for soybean were height of plant, number of mainstem nodes, number of pods, total above ground plant weight, vegetative weight, seed yield per plant, number of seeds per plant, and harvest index (seed wt./total plant wt.). All parameters were measured after the plants were forced air dried.

Height of plant and yield per-plant were the only yield components recorded for corn. The corn per-plant yields were determined for each treatment by dividing the yield per plot by the number of plants harvested per plot.

The corn and soybean rows were hand harvested during the last week of October after trimming each to a uniform length. One-meter lengths at each end of the plots plus the outside crop rows served as border rows. The actual land area harvested was 4.5, 4.0 and 3.4

square meters for the 75, 100, and 130 cm row widths, respectively. The corn ears were dried with forced air to a constant moisture content and then hand shelled. The corn weights were adjusted to a 15.5% moisture and converted to Kg/hectare. Soybeans were mechanically thrashed in the field the day of harvest with a Hege smaller plot research combine. The seed samples were dried with forced air to a constant moisture content, weighted, adjusted to a 13% moisture and recorded as Kg/hectare.

Apparent photosynthesis (AP) measurements were conducted using with radioactive labelled carbon dioxide (7, 27, 30, 36) (analysis, 351 ppm $^{14}CO_2$, 21% O_2, N_2 balance) using the procedure described by Mendoza (28). The procedure entailed exposure of a 1 cm^2 leaf area to $^{14}CO_2$ (specific activity 10.5 μCi/liter) for 20 seconds at a flow rate of 150 ml/minute. The exposed leaf tissue was then removed from the leaf and placed in a 20 ml scintillation vial containing 1 ml of tissue solubilizer (NCS). After a 48 hour digestion period, the leaf tissue was bleached with 1 ml of saturated solution of benzoyl peroxide (1 ml benzoyl perioxide in 5 ml toluene) and 18 mls of scintillation fluid (6 g PPO and 75 mg POPOPO per liter of toluene) were added to each vial. The samples were protected from direct sunlight until they were analyzed with a Beckman LS 8100 Liquid Scintillation Counter (Irvine, Calif.). Counts per minute were converted to mg $CO_2 dm^{-2} hr^{-1}$ using the following formula:

$$BPs = \frac{(cpm - bkgd)\ (\alpha)\ (R)}{(\beta)\quad(\gamma)}$$

Where;

$BPs = CO_2$ uptake (mg $CO_2 dm^{-2} hr^{-1}$)

cpm = counts per minute

bkgd = background counts per minute

α = counting efficiency (80-90%)

R = factor for conversion from cpm to mg CO_2 (3.4×10^{-8})

β = factor for conversion of leaf area from cm^2 to dm^2 (.01)

γ = factor for conversion from seconds to hour (.0056)

Field operations for photosynthesis consisted of taking leaf samples from a randomly selected corn plant for each treatment for two replications. The corn samples were always taken mid-way between the leaf collar to the leaf tip and to one side of the mid-rib from the leaf subtending the ear. At each sampling the incident photosynthet-icly active radiation (PAR) was recorded using a Lambda Instruments L1-185 light meter. All corn sampling took place on September 7, 1978 between 11:30 AM and 2:00 PM EDT.

Two soybean samples were randomly taken from the upper and lower canopy of each treatment for two replications. No effort was made to restrict the sampling from upper and lower canopies of the same plants. Incident PAR measurements were taken at the time of sampling, 11:30 AM to 2:00 PM EDT, September 1-2, 1978, with a Lambda Instruments L1-185 light meter.

Leaf area measurements were made on corn 45 and 81 days after planting (DAP), and on soybeans 45 and 75 DAP. A non-destructive method, as outlined by Sestak et al. (34), was used. This non-destructive method employed linear regression analysis to determine the relationship between actual leaf area (cm^2) and measured leaf dimensions. For corn, the leaf dimension measured was length of the leaf, from the leaf collar to the leaf blade tip. For soybeans, the length and width of the terminal leaflet were measured.

Regression equations for soybean leaf area measurements, regression of the product of length times width on actual leaf area of the trifoliolate, were determined for the 45 and 75 DAP samplings. At each sampling, whole plants were harvested from the border rows of randomly selected plots. For the first sampling the length and width and the actual leaf area of 118 leaves, representing 36 plants from 18 plots, were measured as described earlier for corn. In the second sampling, 140 leaves representing 24 plants and 12 plots, were measured. The regression equations established for the 45 and 75 DAP measurements were:

$$Y = -\ 10.38 + .0209\ (X) \qquad R = .99$$

and

$$Y = 14.22 + .0175\ (X) \qquad R = .98$$

where Y = leaf area in cm^2, and X = product of the length times width of the terminal leaflet. Both equations were significant (.001).

The regression equation for corn, regression of leaf length on actual leaf area, was determined by randomly selecting 33 leaves (3 leaves per plant from 11 plots), measuring the leaf length and placing the leaf in a leaf area meter (Lambda Instruments, Model LI-300) to determine the actual leaf area. The regression equation established and used for both the 45 and 81 DAP was:

$$Y = -\ 509 + 14.8279\ (X)$$

where Y = cm^2 of leaf area, and X = length of the corn leaf. The regression correlation was .92, which was significant (.001).

Corn leaf area measurements in the treatments consisted of measuring the length of every leaf for two randomly selected plants. Four replications were sampled 45 and three replications were sampled 81 DAP. The length values determined from the measurements were converted to leaf area using the established corn regression equation. All individual leaf areas were added together and divided by the respective land area the plants occupied to determine the Leaf Area Index (LAI).

Soybean leaf area determinations consisted of sampling two plants per plot over four replications, and four plants per-plant over three replications, for the 45 and 75 DAP, respectively. The length and width dimensions for the terminal leaflets of all leaves were measured and the leaf height above the ground was recorded. The areas of all individual leaves were summed and divided by the land area the plants occupied to determine LAI.

Photosynthetically active radiation (PAR) was measured at four different vertical depths within the canopy, 1.4, 0.9, 0.45 meters above the ground, and ground level, for both monoculture and polyculture treatments 66 DAP using a hand-held light meter (Lambda Instruments, Model L1-185). At each depth, the horizontal area between the two corn rows were sampled by holding the sensor head as nearly vertical as possible. Six to ten readings were taken at each depth. These readings were converted to percentage of direct sunlight based on the reading in full sunlight above the canopy. All measurements were taken between 11:35 AM and 2:00 PM EDT over two replications on August 4-5, 1978.

RESULTS AND DISCUSSION

Grain Yields

Yields of corn and soybeans in polyculture (Table 1) were always less than their monoculture counterparts. Monoculture corn yields, at high corn population, averaged 9144.3 Kg/ha, while polyculture corn yields averaged over corn populations and soybean spatial arrangements were 6173.5 Kg/ha, 32.5% less. Average monoculture soybean yields were 2758.6 Kg/ha, while average polyculture soybean yields were 1027.7 Kg/ha, or a 62.8% reduction from monoculture (Figure 4).

The polyculture corn yields were significantly affected by corn population and spatial arrangement of the soybeans. The average yield of the high corn population (6907.0 Kg/ha) was significantly (.001) greater than that of the lower corn population (5400.0 Kg/ha) (Figure 5). The corn yield in spatial level three (6896.5 Kg/ha) was significantly (.01) greater than that of levels one (5783.0 Kg/ha) and two (5841.0 Kg/ha) (Figure 6).

The soybean yield response was more complicated than that of the corn. All three main effects, corn population, corn row width, and soybean spatial arrangement significantly (.001, .001, and .01, respectively) affected the soybean yield. Analysis of the three-factor interaction provided the clearest explanation of the soybean yield response to different treatments.

Table 1.--The grain yield (Kg) per hectare for corn and soybeans as influenced by corn population, corn row width, and soybean spatial arrangement.

YIELDS OF CORN AND SOYBEANS
IN POLYCULTURE

		CORN ROW WIDTH					
		75 cm		100 cm		130 cm	
SPATIAL	POP	CORN	SOYBEAN	CORN	SOYBEAN	CORN	SOYBEAN
1	1	6342.2	973.2	6156.9	861.7	6625.0	808.8
	2	4953.0	1454.1	4574.4	1538.3	6045.6	1167.6
2	1	6705.3	922.0	6733.8	958.3	6708.1	750.0
	2	4734.7	1347.6	5381.3	1061.7	4783.1	931.4
3	1	8334.3	675.6	7358.1	916.7	7191.9	694.1
	2	5778.9	1461.0	6313.1	1021.7	6398.6	953.9

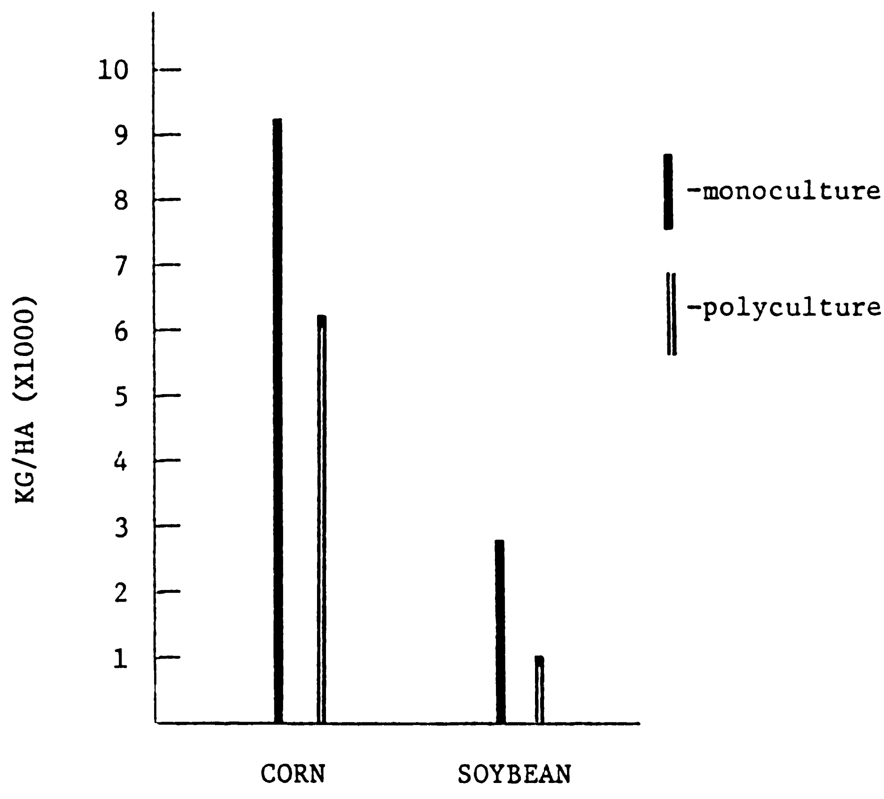

FIGURE 4. The average yield of corn and soybeans in monoculture and polyculture cropping systems.

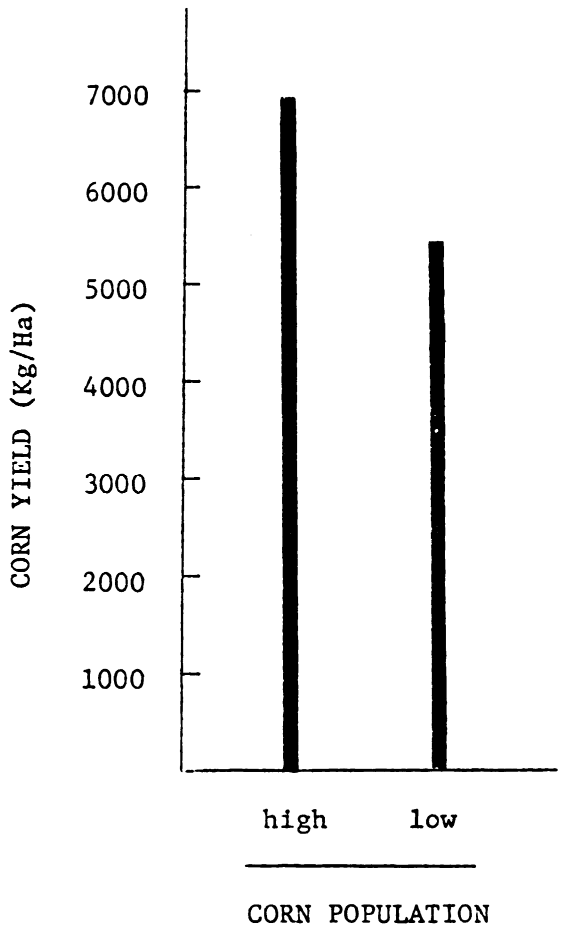

FIGURE 5. Effects of corn plant population on the average yield of corn in polycultures.

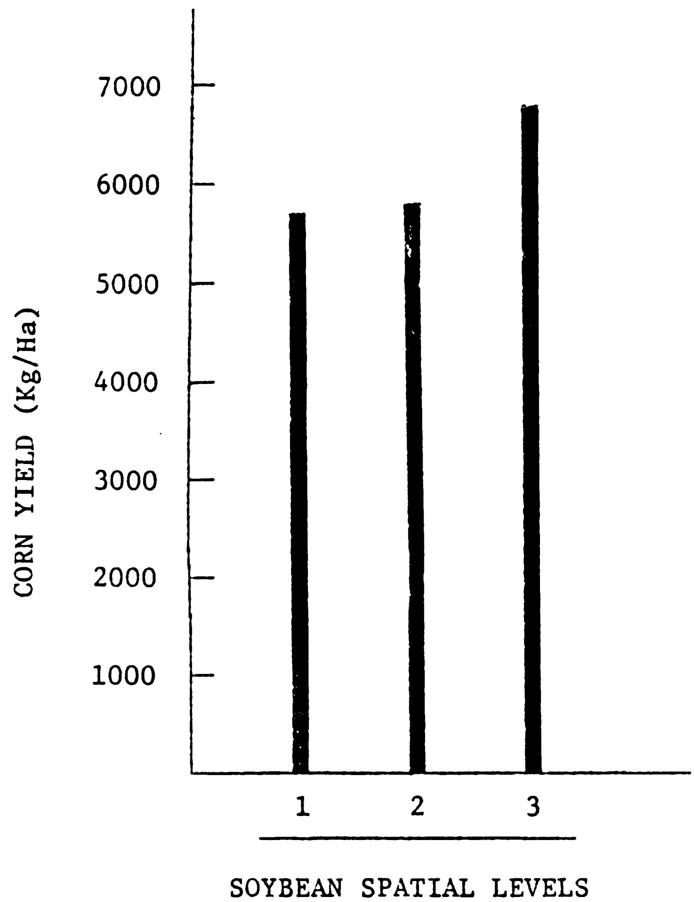

FIGURE 6. Effects of soybean spatial arrangement (averaged over corn populations and row widths) on the yield of corn in polyculture.

Most of the variability in the three-way interaction, which was significant at the 5% level, can be explained in terms of corn population and corn row width (Table A2), while soybean spatial arrangement accounted for only a small amount of the soybean yield variability. The soybean yield response to a reduction in corn population was much greater in the 75 cm row width (65% increase) than in either the 100 or the 130 cm row widths (32 and 35%, respectively), but the yield increase was not equally distributed over all three spatial levels. Spatial levels two and three yielded much more in the 75 cm row width than in either the 100 or the 130 cm row width when corn population decreased (Figure 7).

There was no statically significant different between the total productivities of the monoculture and polyculture systems, but there was a slightly significant difference within polyculture productivities (.10). The Land Equivalent Ratio (LER) values ranged from .90 for low corn population, 130 cm row width, and second soybean spatial level, to 1.22 for high corn population, 75 cm row width, and third soybean spatial level (Table 2).

The relative productivities of the polycultures, as measured by the LER values, were influenced more by the soybean spatial arrangement than by either corn population or corn row width. Spatial level three had the largest LER with 1.13, while spatial levels one and two had LER's of 1.04 and 1.03, respectively. The corn population times soybean spatial arrangement interaction was significant at the 10% level only, with the low corn population giving a higher LER at spatial level one only (Figure 8).

The interaction between corn population and soybean spatial

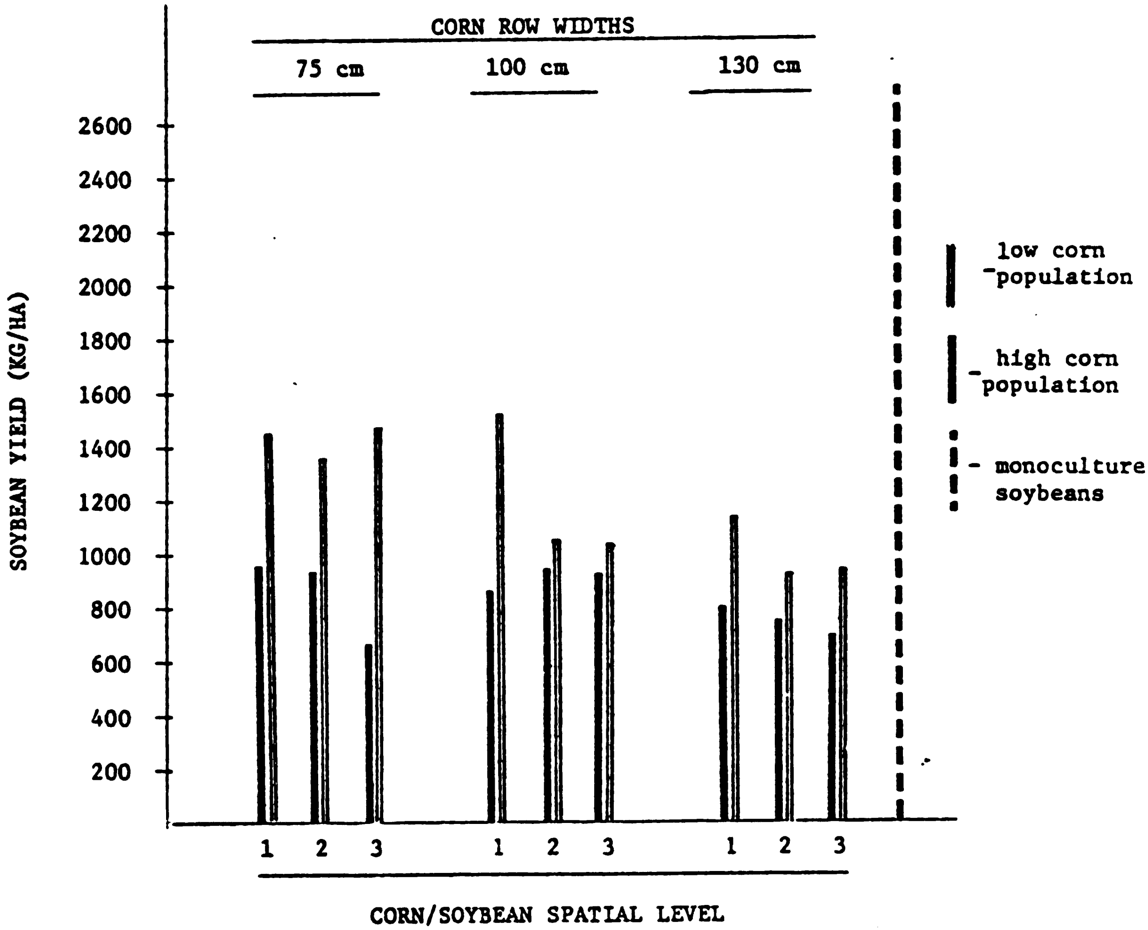

FIGURE 7. Yield of soybeans as affected by corn row widths, corn population and soybean spatial arrangements.

Table 2.--Land Equivalent Ratio (LER) as affected by corn population, corn row width, and corn/soybean intimacy level.

LAND EQUIVALENT RATIO

		CORN ROW WIDTH (cm)					
		75		100		130	
	POP.	high	low	high	low	high	low
CORN/ SOYBEAN INTIMACY LEVEL	1 (MAXIMUM)	1.03	1.12	0.98	1.07	1.02	1.13
	2 (MEDIUM)	1.07	1.00	1.15	1.02	1.03	0.90
	3 (MINIMUM)	1.22	1.16	1.17	1.05	1.09	1.10

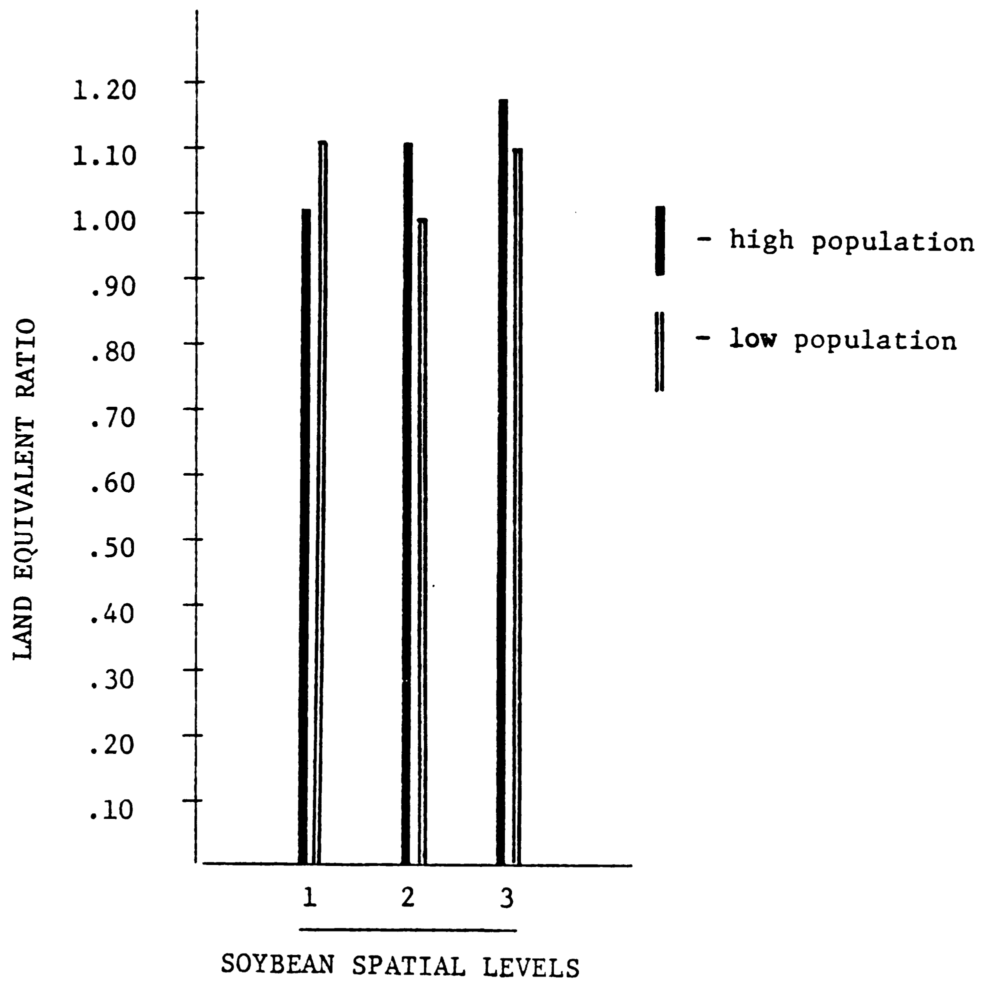

FIGURE 8. Effects of corn population and soybean spatial arrangement on the polyculture system productivity (LER).

arrangement suggested that system productivity was largely determined by the relationship between corn intra-specific competition and corn/soybean inter-specific competition, while soybean intra-specific competition played only a minor role in determining total yield.

A general estimate of system inter-specific competition was derived from per-plant corn yields. The corn plant densities varied between 26,000 and 30,000 plants per hectare at the low population, while at high densities the corn populations were plus or minus 5,000 plants/hectare of the desired 45,000 plants/hectare. Soybean plant densities were always less than the desired level of 300,000 plants/hectare, ranging from 190,000 to 200,000 plants/hectare. Based upon the assumption that per-plant corn yields accurately reflected the level of monoculture intra-specific competition, and that per-plant yield of corn decreased linearly as population increased, a population-dependent potential for per-plant corn yield was predicted for each polyculture spatial level at both high and low corn populations. The difference between potential per-plant yield and actual polyculture per-plant corn yield was attributed to the presence of the soybeans, and therefore, represented the magnitude of inter-specific competition. The per-plant corn yields are shown in Figure 9. Estimated maximum per-plant yield potential were derived by connecting monoculture per-plant yields for populations one and two. The actual polyculture per-plant corn yields are also shown. Figure 9 shows that per-plant corn yields were generally lower at higher corn populations regardless of corn/soybean spatial arrangement. The different between the actual polyculture per-plant yields and the potential monoculture per-plant yields are presented in Figure 10. The height of the bars on this

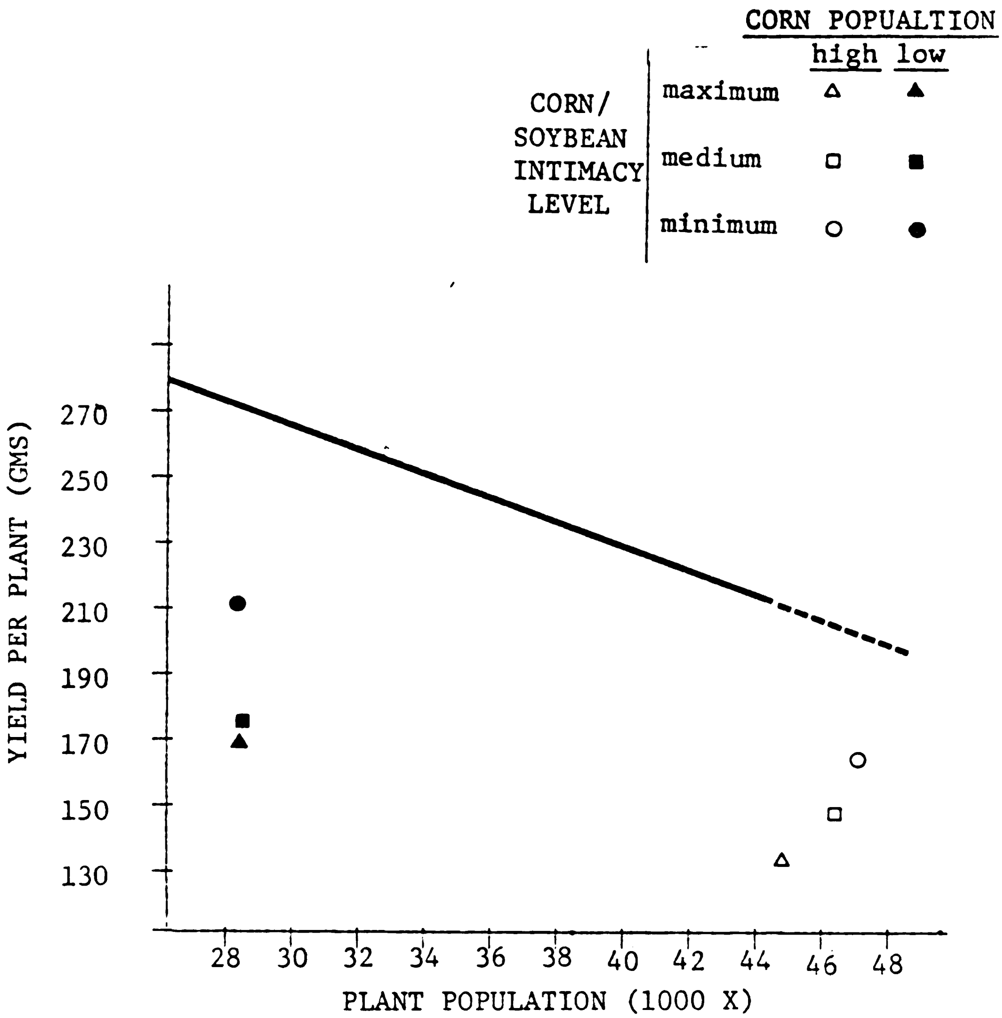

FIGURE 9. Effects of corn population and soybean spatial level on the yield per plant of corn.

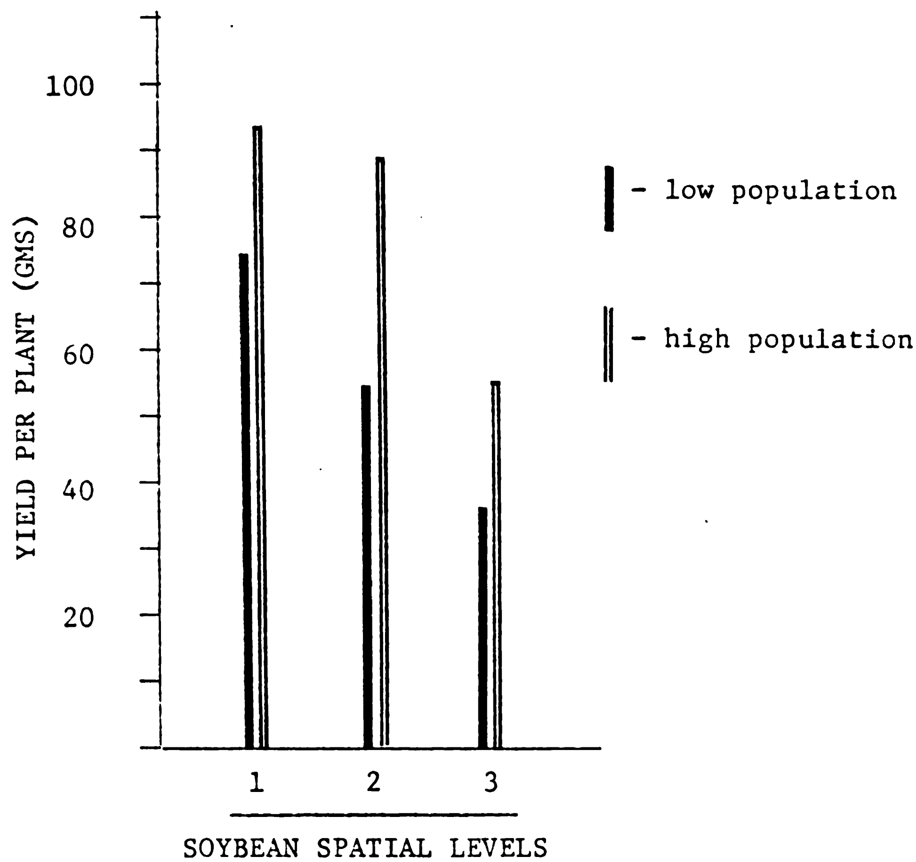

FIGURE 10. Differences between potential and actual corn yield/plant at the three soybean spatial arrangements and two corn populations averaged over corn row widths.

figure were assumed to directly reflect the level of system inter-specific competition. The greatest departure from monoculture yield was 95 grams at the low corn population and the most intimate corn/soybean spatial arrangement.

The influence of inter-specific competition on system productivity was determined by the level of corn intra-specific competition (Figure 10). At high levels of corn intra-specific competition (high population), the system productivity (LER) increased from 1.01 to 1.16 as inter-specific competition decreased (Figure 8). System productivity, at low levels of corn intra-specific competition, remained constant at both high and low levels of inter-specific competition, but decreased at intermediate levels of inter-specific competition as shown in Figure 8. The differential system productivity response between levels of corn intra-specific competition appears to have been caused by a change in the relative contribution of corn and soybean yields to the total productivity at different levels of inter-specific competition.

The total system productivity at high levels of corn intra-specific competition was attributed to an enhancement of the corn's competitive status as inter-specific competition decreased. The productivity of these high corn population polycultures increased as the spatial distance between the corn and soybean rows increased. Corn's greater physical stature at high populations and its generally more dominate competitive ability caused it to utilize a larger portion of the available growth factors at the higher populations. This resulted in a significant increase in corn yields at high corn populations compared to low corn population yields. Therefore, the corn's yield constituted a larger portion of the total productivity than did that of soybeans. The productivity (LER) of each high population polyculture system has been partitioned into the relative contribution of each crop and is shown in Figure 11. The portion that corn yield contributed to the system's LER increased as the distance between corn and soybean rows increased (less inter-specific competition), while soybean's contribution varied only slightly at the high corn populations. Corn yield constituted approximately 68, 73, and 77% of final productivity in spatial levels 1, 2, and 3, respectively, and soybean yield contribution remained constant at approximately 32% for each spatial level at high corn population.

These results suggested the presence of a productivity-limiting level of inter-specific competition. The high corn population at the most intimate species association (corn and soybean crop rows closest together) would presumedly exhibit the highest degree of inter-specific competition under these experimental conditions (Figure 10). As was shown, the productivity increased as the level of inter-specific competition decreased. Possibly, the productivity trend can be continued by further decreasing inter-specific competition.

System productivity at low levels of corn intra-specific competition (low corn population) was positively affected (LER greater than 1.0) by both low and high levels of inter-specific competition (spatial three and one, respectively) as can be seen in Figure 8. This seemingly contradictory response can be explained in terms of LER composition, which changes with the level of inter-specific competition. The LER's for the first and third spatial arrangement were approximately equal (Figure 11), but the relative contribution of corn and soybeans

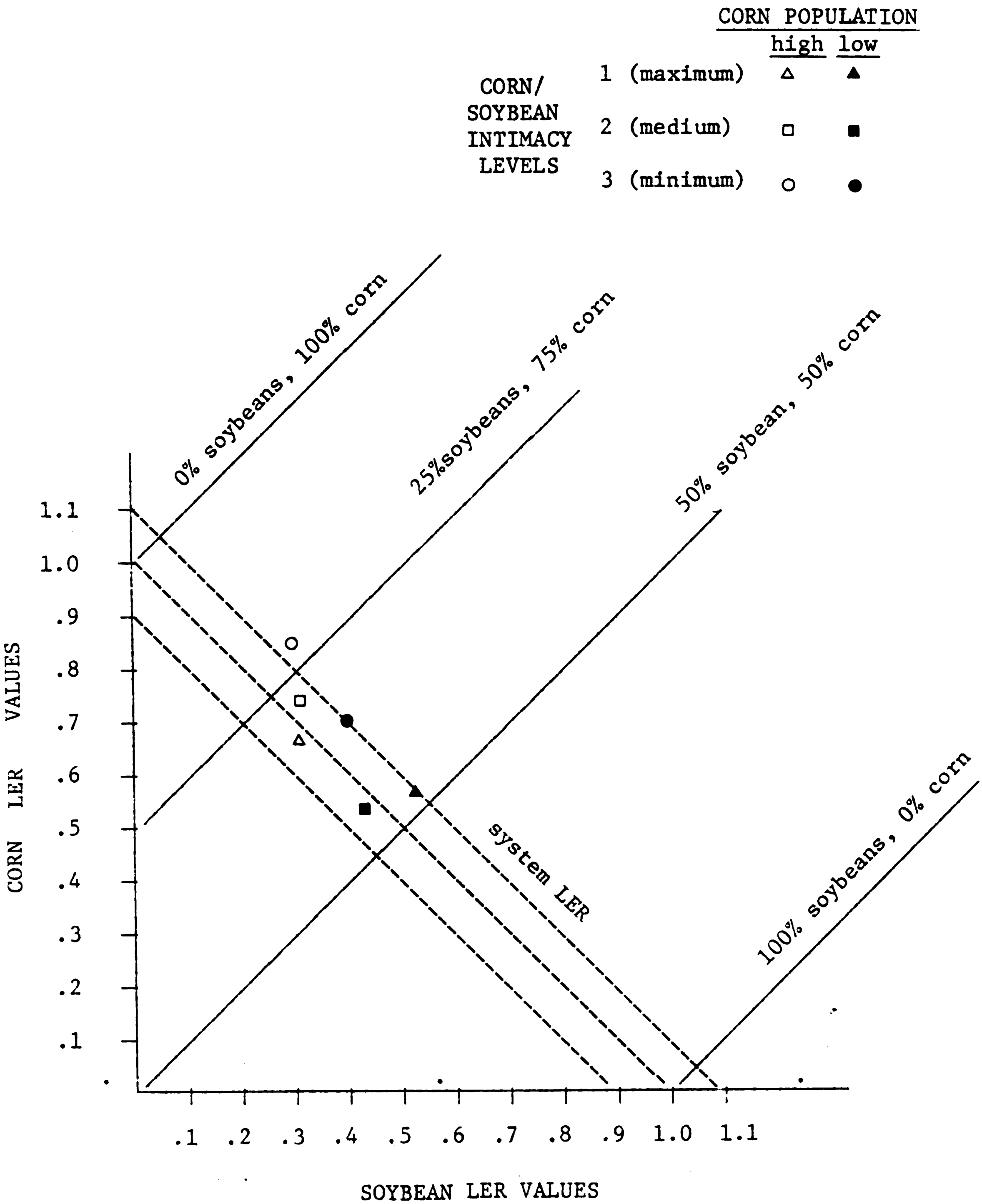

FIGURE 11. The relative contribution of both soybeans and corn to the total Land Equivalent Ratio (LER) averaged over corn row widths. Negative slopes indicates system LER and positive slopes indicates percent contribution of corn and soybeans.

to the system LER changed. Corn comprised 52 and 63% of the system LER at spatial levels one and three, respectively, while soybean yields accounted for 48 and 37%, respectively. At low corn population the highest level of inter-specific competition occurred in spatial level one, the lowest in spatial level three. This corresponded to the occurrence of significant yield changes in soybeans and corn, respectively. Soybean yields in spatial level one were significantly greater than in levels two or three, while corn yields in spatial level three were significantly greater than in spatial level one or two (Figures 6 and 12). This shows that soybeans benefited when inter-specific competition was high (spatial level one) and that corn yields suffered, while the opposite was true in the third level where inter-specific competition was low.

This reciprocal relationship between corn and soybeans, where one crop's yield compensated for the drop in the other's yield, suggested that the level of inter-specific competition will determine the competitive status of the polyculture crops. If this assumption is correct, it would suggest that the yield magnitude of corn and soybeans in a polyculture system can be manipulated somewhat without sacrificing total system productivity. The LER value at the intermediate spatial arrangement suggested that neither corn nor soybeans was given a clear competitive edge, hence the system productivity decreased.

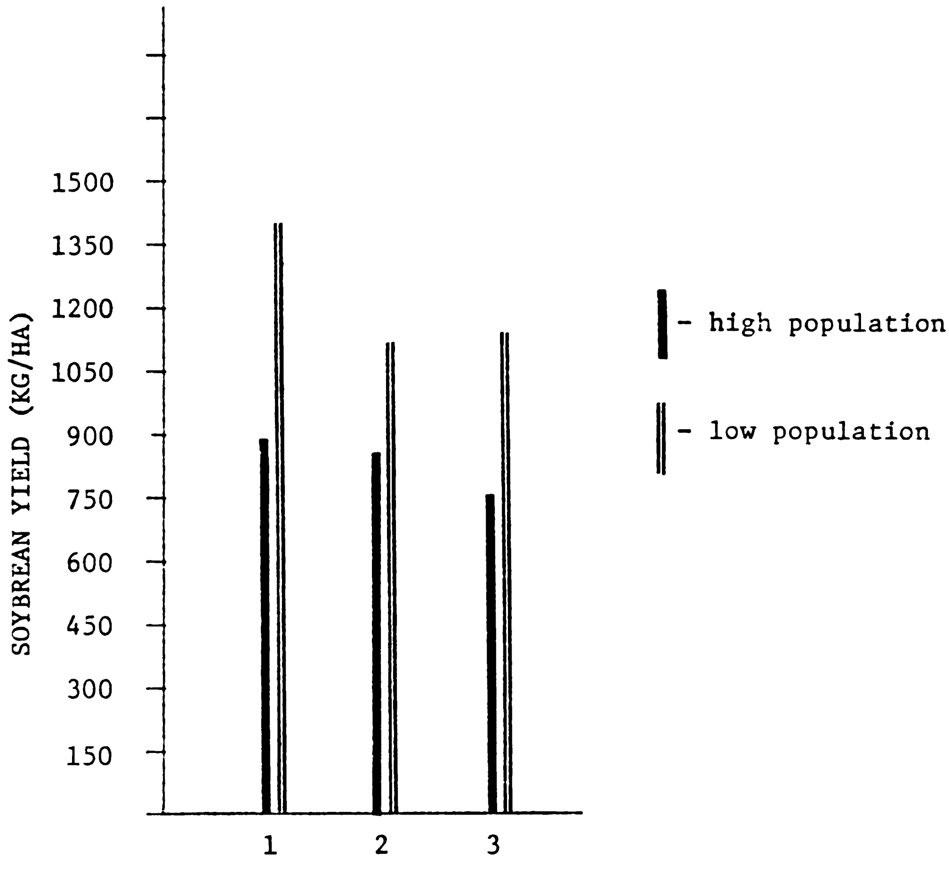

FIGURE 12. Effects of corn population and soybean spatial arrangements (averaged over corn row widths) on soybean yields in polyculture.

Components of Yield--Soybeans

The polyculture components of yield values for soybeans from this experiment were, in general, characteristic of soybean plants grown under low light regimes. Corn population was the only factor which significantly affected polyculture soybean's components of yield values. Except for plant height, monoculture soybean values were always much greater than polyculture values, and soybean values under low corn population were generally greater than under high corn population (Table 3).

Those values per-plant which increased significantly (.001) between high and low corn population averaged over corn row widths and soybean spatial arrangement, were for high and low corn population, respectively: mainstem nodes, 11.7 vs 12.8; total plant weight, 12.4 vs 15.9 grams; vegetative weight, 6.3 vs 7.8 grams; and seed weight, 6.1 vs 8.1. Significant at the .01 level were number of pods per-plant, 17.0 vs 19.8 and number of seeds per-plant, 34.0 vs 42.0. Harvest index, significant at the .05 level, increased from .49 at the high corn population to .51 at the low corn population. Soybean plant height and lodging were not significantly affected by any treatment of combination of treatments.

Plant height differences between monoculture and polyculture and within polycultures was partially a result of greater internodal elongation in the polyculture treatments, but was non-significant. Monoculture soybeans height averaged 102.0 cm per-plant with 16.5 nodes, while soybeans in high and low corn population polyculture averaged 102.0 and 108.4 cm, with 11.7 and 12.8 nodes, respectively.

Table 3.--Effects of corn populations on the components of yield for soybeans in polyculture, averaged over corn row widths and soybean spatial arrangements, and the components of yield for soybeans in monocultures.

COMPONENTS OF YIELD FOR SOYBEANS

	POPULATION	PLANT LENGHT (cm)	MAINSTEM NODES	NUMBER OF PODS	PLANT WEIGHT (g)	VEGETATIVE WEIGHT (g)	SEED WEIGHT (g)	NUMBER OF SEEDS	HARVEST INDEX
LEVEL OF SIGNIFICANCE		ns	.001	.01	.001	.001	.001	.01	.05
POLYCULTURE	HIGH	102.8	11.7	17.0	12.4	6.3	6.1	34.5	.49
POLYCULTURE	LOW	108.4	12,8	19.8	15.9	7.8	8.1	42.0	.51
MONOCULTURE		102.0	16.5	34.2	36.0	17.3	18.8	102.0	.52

The average length of soybean internodes at high and low corn population were similar at 8.7 and 8.5 cm, respectively, while monoculture internode length was 6.2 cm.

Components of Yield--Corn

The components of yield for corn, yield per-plant and plant height, were larger for the monoculture system than for the polyculture system. Yield of monoculture corn at high corn population was 208 g/plant, while average polyculture yield per-plant decreased 19% to 168.3 grams. Plant height was 212.7 cm and 200 cm for monoculture and polyculture corn, respectively.

Within polycultures, corn yield per-plant was significantly (.01) affected by corn population, increasing from 148.3 grams at high corn population to 188.2 g/plant at low corn population. Soybean spatial level also affected the per-plant yield of polyculture corn (.05) averaged over corn populations and row widths, the corn yields were 156.9, 161.4, and 186.5 g/plant in spatial levels one, two, and three, respectively (Figure 13).

Height of corn plants in polyculture were not significantly affected by any treatment or treatment combination.

Light Attenuation

Results of light penetration measurements showed that corn population and corn row width significantly (.05 and .001, respectively) affected the amount of light at the 1.4 and .85 meter heights in the

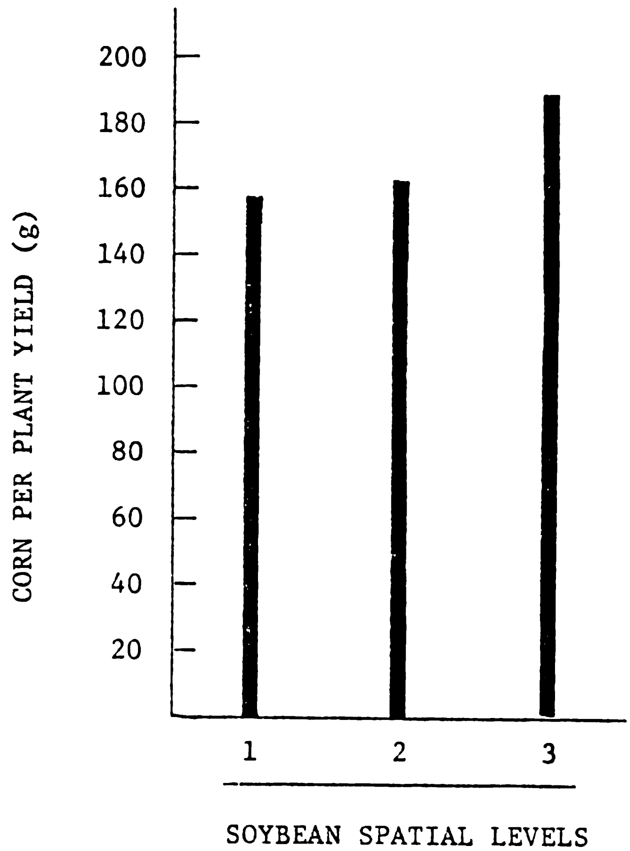

FIGURE 13. Effects of soybean spatial arrangement (averaged over corn populations and row widths) on the corn per plant yield.

canopy, respectively. The percent of total light at the 1.4 meter height in the polyculture canopy was 52 and 63% under high and low corn population, respectively. At the .85 and .45 meter heights in the canopy, the amount of total sunlight was uniformly reduced to the extent that it was not significantly affected by corn population, corn row width, or soybean spatial arrangement (Figure 14). Monoculture corn at high population had 51 and 40% of total sunlight at the 1.4 and .85 meter height, respectively.

Figure 15 shows that the 75 cm row width had the least amount of total sunlight at the .85 meter height, at 30%, while the 100 and 130 cm row widths had 36 and 47% of total sunlight, respectively. There was no significant difference in the amount of total sunlight at the 1.4 and .45 meter heights in the canopy. This might be expected, since the upper canopies all received more than 50% of the incoming radiation and the lower levels were all quite shaded.

Crop Development

Height

The height of polyculture corn 45 days after planting (DAP) was significantly affected by soybean spatial arrangement (.05). Spatial level three (minimum corn/soybean intimacy level) was tallest, 114 cm, followed in order by spatial levels two and one, with 107 and 105 cm, respectively (Figure 16). Monoculture corn height was 122 cm. By 81 DAP there was no significant difference in corn plant height within polycultures. Monoculture and polyculture corn plant heights

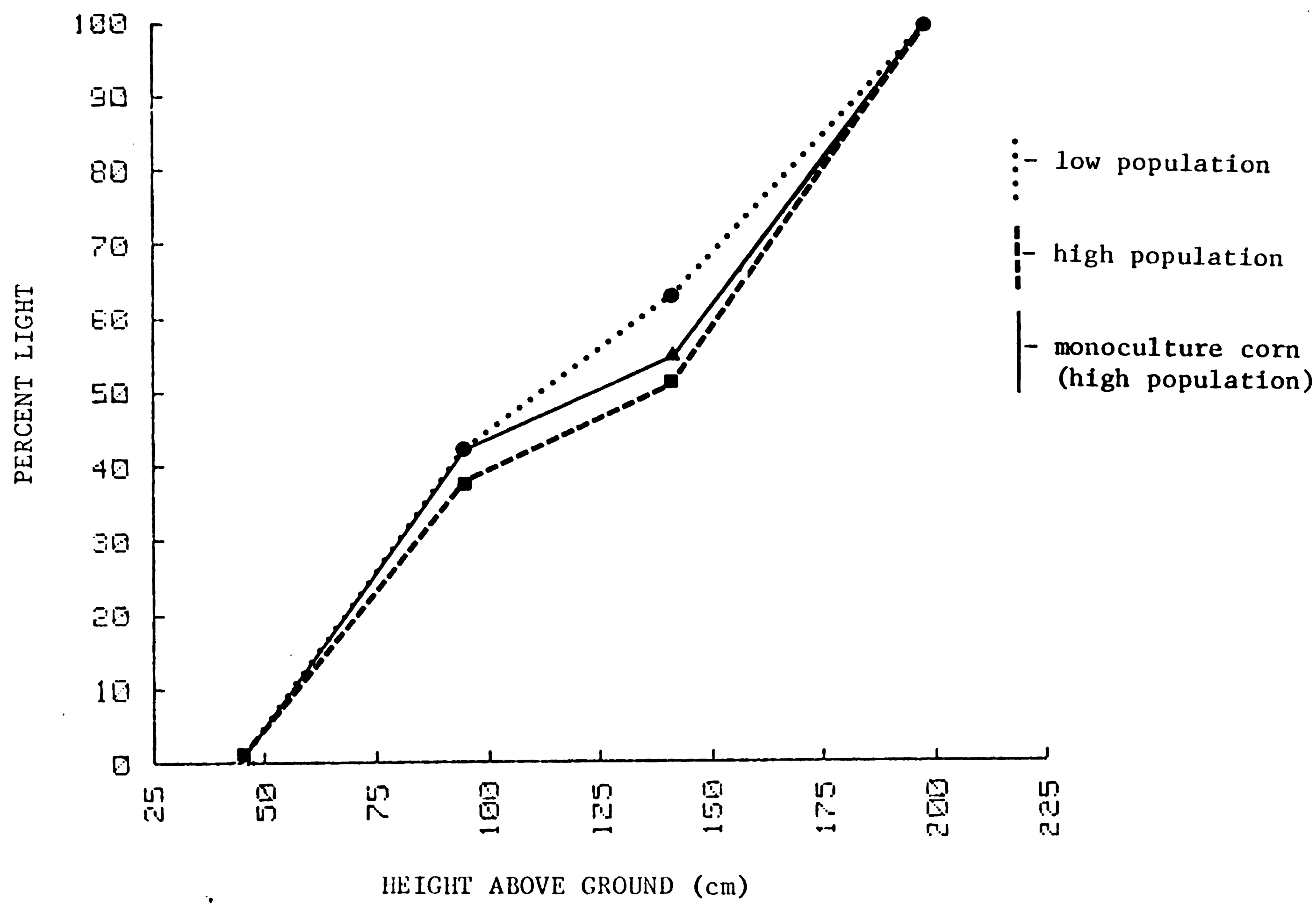

FIGURE 14. Effects of corn populations on the attenuation of light through a polyculture canopy, and light attenuation through the canopy of monoculture corn at high population.

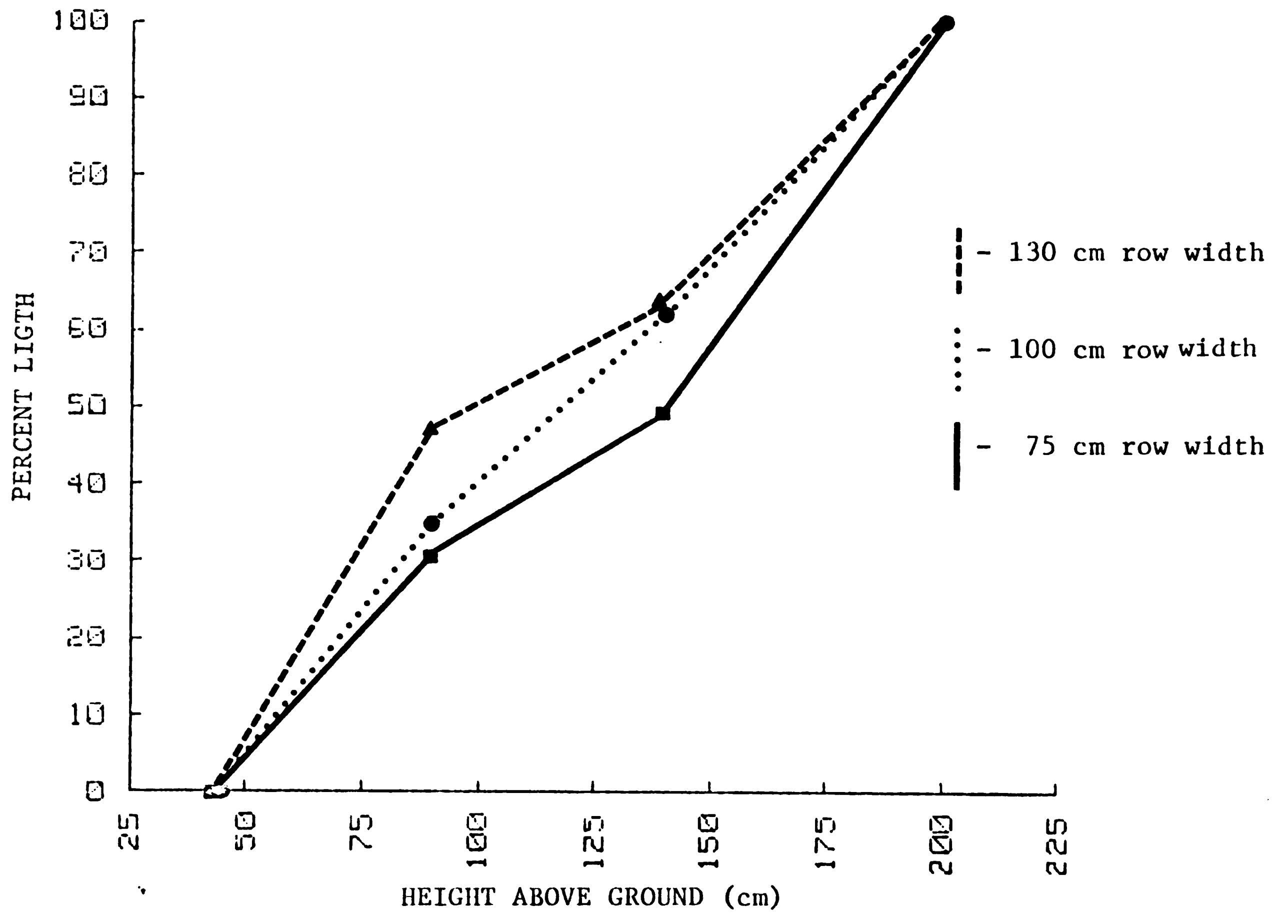

FIGURE 15. Effects of corn row widths on the attenuation of light through the polyculture canopy, averaged over soybean spatial arrangements.

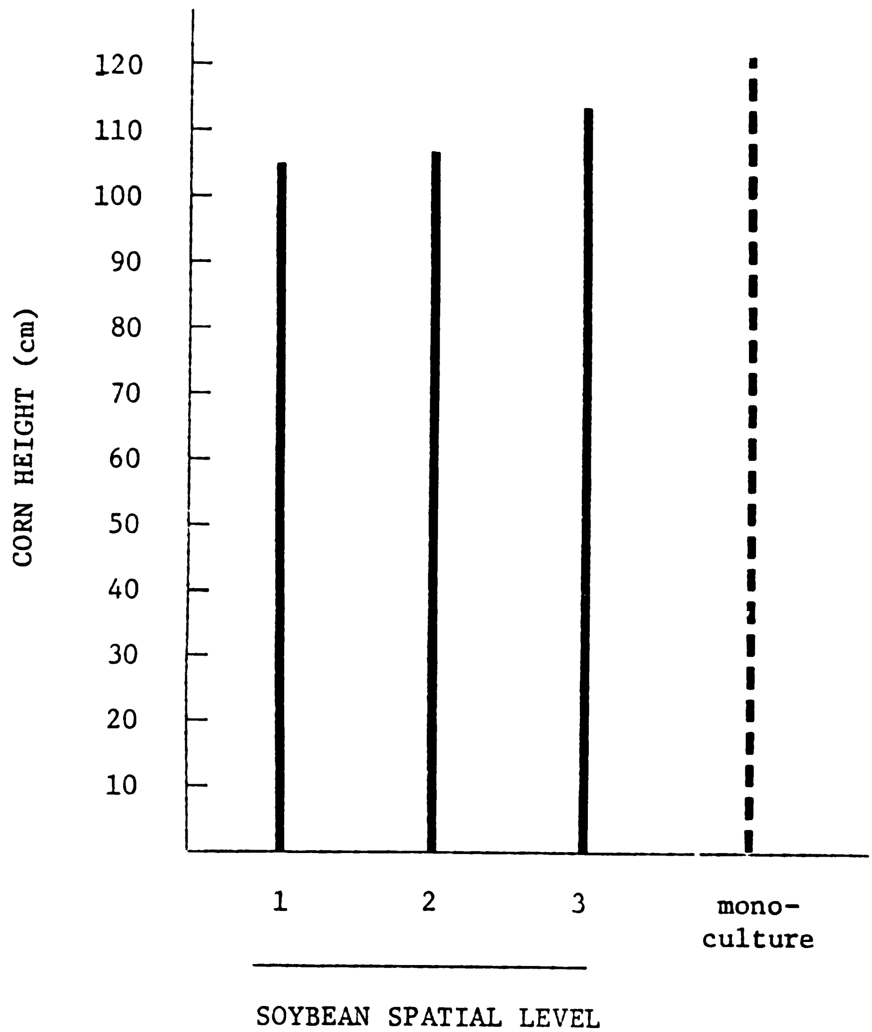

FIGURE 16. The height of corn 45 days after planting as affected by soybean spatial level averaged over corn row widths and corn population, and the height of corn in monoculture, averaged over high and low populations.

were 212.7 and 200 cm, respectively.

The height of soybean plants 45 DAP was significantly affected by corn population (.05) and by soybean spatial arrangement (.05). The height of the soybean plants under high and low corn population treatments were 30.8 and 29.3 cm, respectively. Spatial level one, two, and three had heights of 29, 30, and 31 cm, respectively. Monoculture and polyculture soybean plant heights were 26 and 30 cm, respectively.

By 75 DAP there were no significant differences in the heights of polyculture soybean plants. Monoculture plants were 102 cm tall while the average height for polyculture plants was 108 cm.

Number of Leaves

The number of leaves for polyculture soybean plants 45 DAP was not significantly affected by any treatment or treatment combination. Monoculture and polyculture plants had 6.6 and 7.4 leaves per-plant, respectively. By 75 DAP the number of leaves per soybean plant was significantly affected by the corn population. Soybean plants under high and low corn populations had 15.0 and 17.8 leaves per plant, respectively. Monoculture soybeans had 21.5 leaves per-plant.

Leaf Area Index

The leaf area index (LAI) for polyculture corn 45 DAP was significantly (.01) influenced by the combination of corn population, corn row width, and soybean spatial arrangement. However, the major

portion of the variability within polyculture corn could be explained by the corn population. The LAI of polyculture corn 81 DAP was significantly affected by population (.001), row width (.001), and soybean spatial arrangement (.01). Again, the major portion of the variability could be explained in terms of corn population. High and low corn population LAI's 81 DAP were 2.66 and 1.79, respectively (Figure 17). This represented an increase of 48.6% for the high corn population. The 130 cm corn row width had an LAI of 2.47, followed by the 75 and 100 cm row widths with values of 2.33 and 1.97, respectively (Figure 18). Figure 19 shows that spatial level three (the minimum corn-soybean intimacy level had an LAI of 2.45, spatial levels two and one had LAI's of 2.13 and 2.09, respectively. Monoculture corn 81 DAP had an LAI of 3.06.

The LAI of polyculture soybeans 45 DAP was significantly (.05) affected by the combination of corn population, corn row width, and soybean spatial arrangement. However, by 75 DAP the three-factor interaction which occurred at 45 DAP had changed to a less complicated condition where one main effect, corn row width, was significant (.001) and one two-factor, corn row width times soybean spatial arrangement, was significant (.05). For soybeans 75 DAP, the LAI's in the 75, 100, and 130 cm row widths, averaged over both corn population (Figure 18), were 3.29, 2.89, and 2.50, respectively. This agrees with the general observation that shaded conditions usually result in expanded leaf blades. For the corn row width times soybean spatial arrangement interaction (Figure 20) the LAI's in the 75 cm row width were 3.11, 3.18, and 3.56, in spatial levels one, two and three, respectively. The reverse occurred in the 100 and 130 cm row width, with soybean

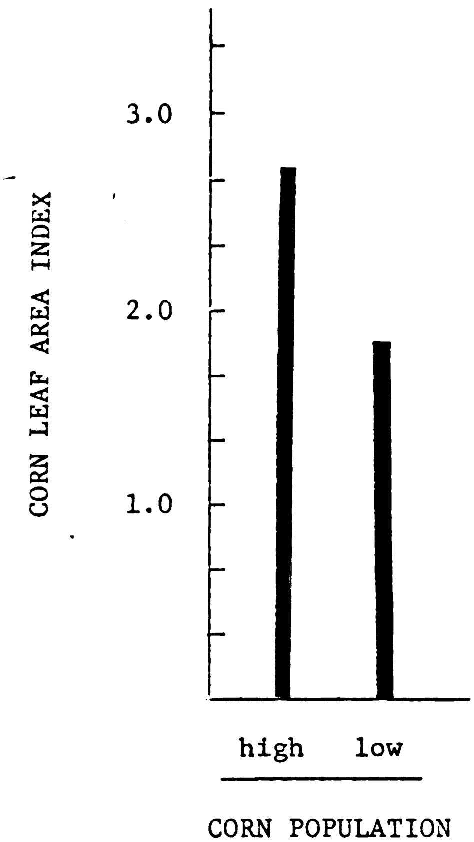

FIGURE 17. Effects of corn population on the LAI of corn in August, 1978, averaged over corn row widths and soybean spatial arrangements.

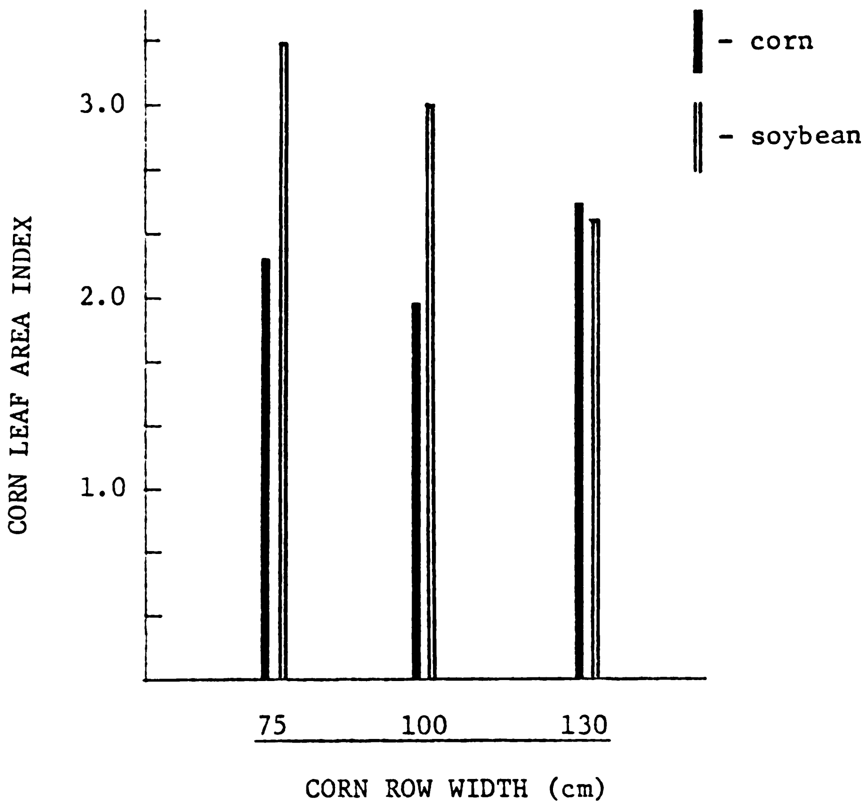

FIGURE 18. Effects of corn row width on the LAI of corn and soybean in August, 1978, averaged over corn populations soybean spatial arrangements.

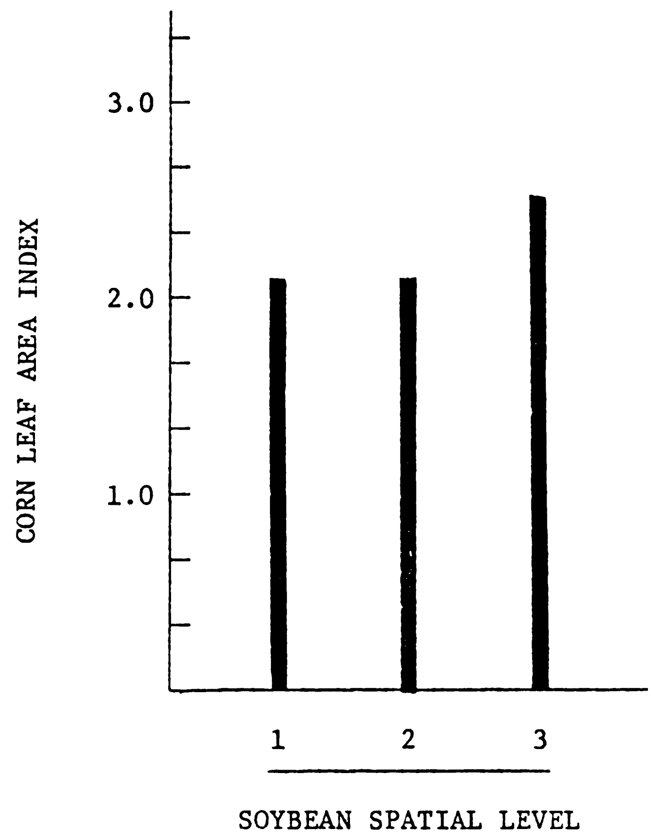

FIGURE 19. Effects of soybean spatial arrangement on corn LAI in August, 1978, averaged over corn populations and corn row widths.

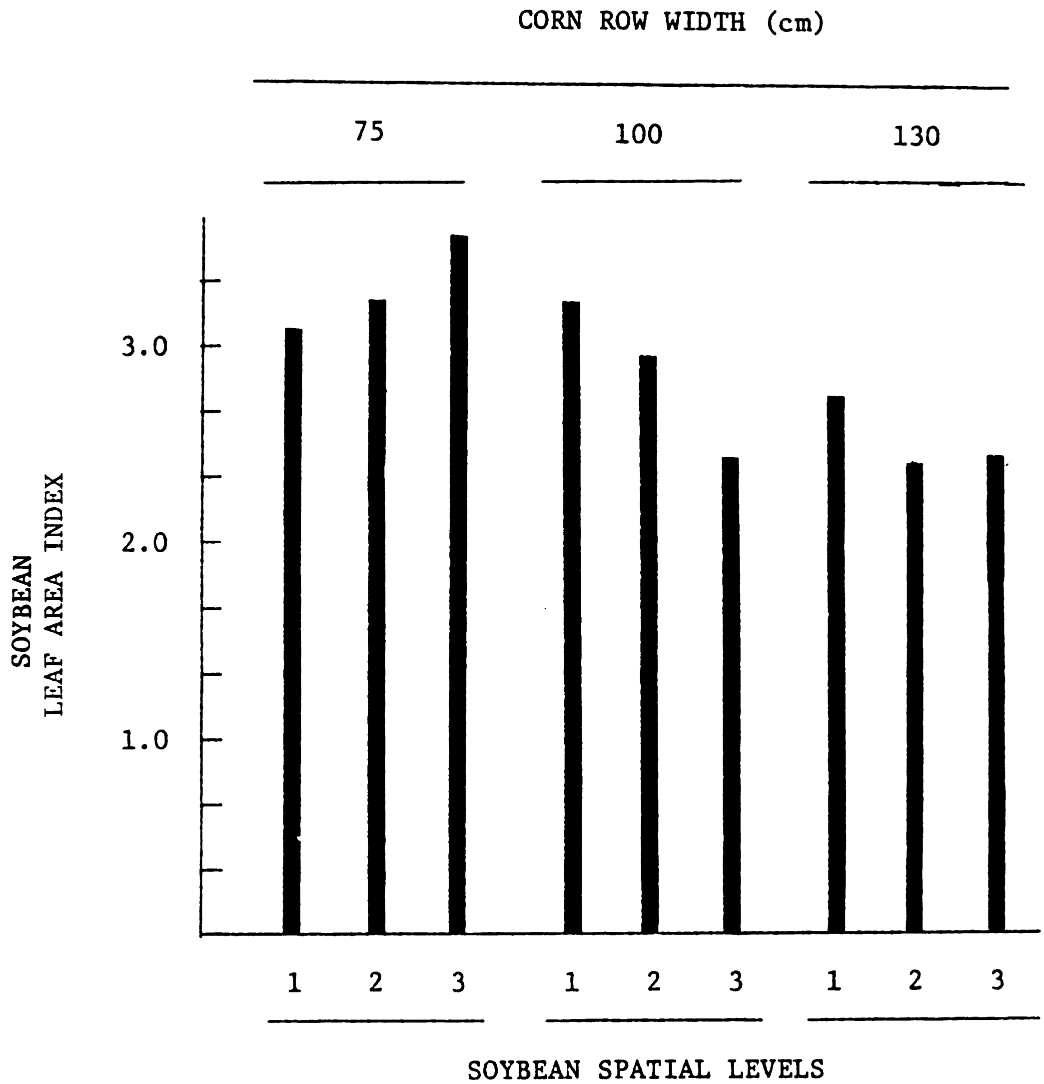

FIGURE 20. Effects of corn row width and soybean spatial arrangements on the LAI of soybeans, averaged over corn populations, 75 days after planting.

LAI's decreasing from spatial levels one to three. In the 100 cm row width, soybean LAI's in spatial level one, two and three were 3.18, 3.04, and 2.44 while the 130 cm row width had soybean LAI's of 2.70, 2.35, and 2.43, respectively.

Photosynthesis

Results of photosynthesis measurements are presented in Figures 21 and 22 and show that the apparent photosynthesis (AP) for high population monoculture corn was 14.5 mg $CO_2dm^{-2}hr^{-1}$, while polyculture corn rates averaged 8.9 mg $CO_2dm^{-2}hr^{-1}$, a 38.6% reduction. Although the monoculture AP rates appears to be very low, this low AP rate was attributed to the late date of sampling (100 days after planting) and agrees with results reported by several other researchers (5, 41, 30).

Monoculture soybean plants averaged 19.81 and 4.89 mg $CO_2dm^{-2}hr^{-1}$ for the top and bottom canopy levels, respectively, while average top and bottom canopy AP rates for polyculture soybeans were 9.17 and 1.2 mg $CO_2dm^{-2}hr^{-1}$, and 51 and 75% reduction, respectively, from the rates for monoculture soybeans.

Differences in the rates of AP were statistically non-significant within polyculture corn treatments and for the lower canopy levels of the polyculture soybeans. The rates of AP for the upper soybean canopy levels were significantly affected by corn population (.01), and by the combination of corn population and soybean spatial arrangement (.05). The soybean AP rates under high and low corn populations when averaged over corn row widths and soybean spatial arrangements, were 6.7 and 12.6 mg $CO_2dm^{-2}hr^{-1}$, respectively (Figure 23). In the

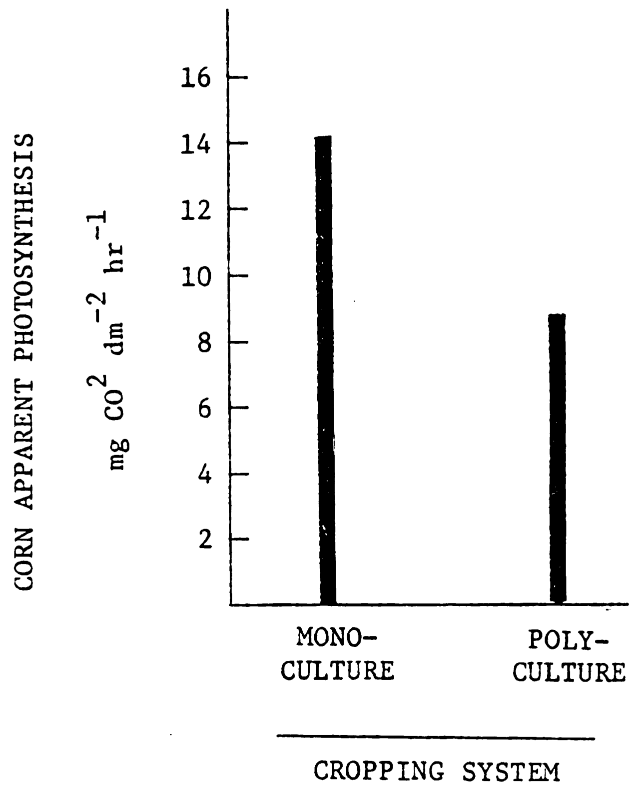

FIGURE 21. The average apparent photosynthesis rate of corn in the monoculture and the polyculture cropping systems.

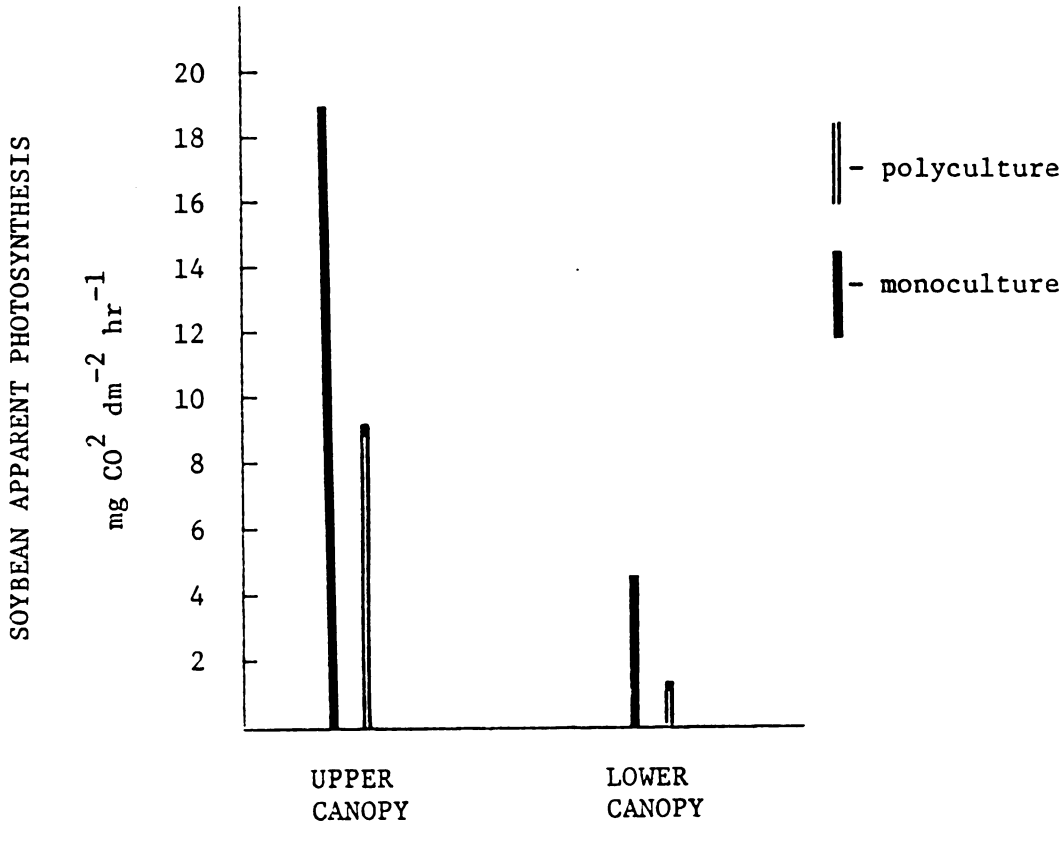

FIGURE 22. The average rate of apparent photosynthesis for soybeans in monoculture and polyculture and at two heights in the soybean canopy.

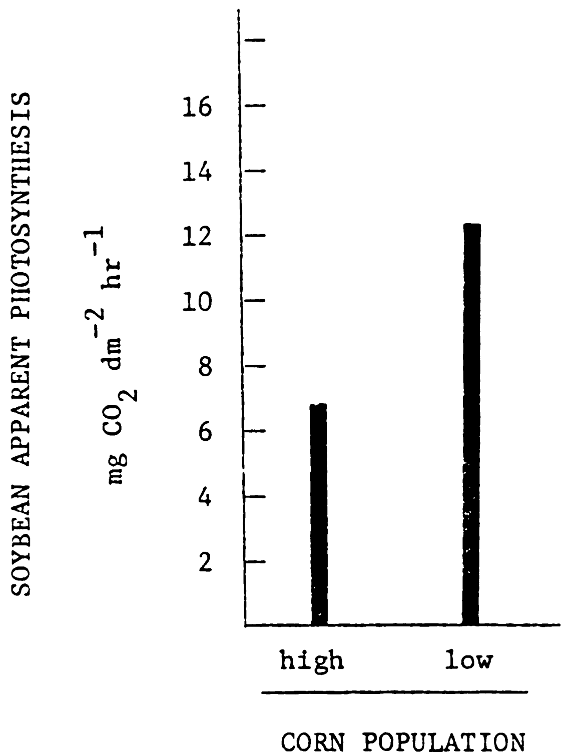

FIGURE 23. Effects of corn population on the rates of apparent photosynthesis of soybeans.

corn population times soybean spatial arrangement interaction, the soybean AP rate at the high corn population decreased steadily from spatial level one to three, 8.4, 7.4, and 4.5 mg $CO_2dm^{-2}hr^{-1}$, respectively, as shown in Figure 24. The reverse occurred under low corn population, with soybean AP rates increasing from 8.0 to 13.2 to 16.6 mg $CO_2dm^{-2}hr^{-1}$ in spatial levels one, two, and three, respectively (Figure 24).

The response of soybean AP rate to inter-specific competition was dependent upon the level of corn intra-specific competition. Figure 24 shows that soybean AP rates decreased from 8.4 (spatial level 1) to 4.5 mg $CO_2dm^{-2}hr^{-1}$ (spatial level 3) as inter-specific competition decreased under high levels of corn intra-specific competition (high corn population). Under low levels of corn intra-specific competition (low corn population) the AP rates of polyculture soybeans increased from 8.0 to 16.6 mg $CO_2dm^{-2}hr^{-1}$ in spatial levels one and three, respectively, a change of over 100%.

Interestingly, the magnitude of corn and soybean yield reduction between monoculture and polyculture was roughly equivalent to the reduction in AP rates between monoculture and polyculture for each crop. The AP rate of polyculture soybean decreased 63% from monoculture rates as yield decreased 62.8%. Polyculture corn AP rates decreased 38.6% as yield decreased 32.5% from monoculture levels.

The near identical rates of AP and yield reduction in soybeans could be explained in a "Law of the Minimum" framework. All factors needed for plant growth may have been in adequate supply except light. If this were true, any change in the quantity of light would result in a proportional change in yield. This reinforces the supposition that

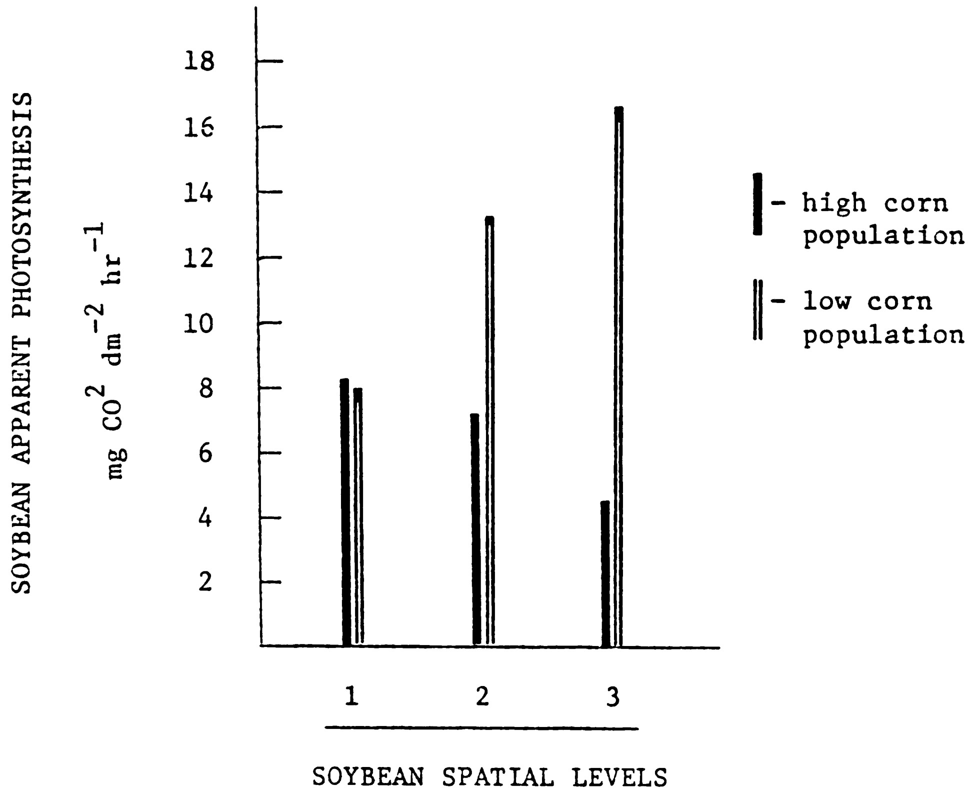

FIGURE 24. Effects of corn populations and soybean spatial arrangement on the rate of apparent photosynthesis for soybeans.

soybeans were responding to the environment created by the corn.

The relationship between corn AP rates and yield resembled the soybean AP/yield relationship, but it would appear that light was probably not the limiting factor. The reduction in soybean AP rates could be directly attributable to the shading by corn, but the corn polyculture AP rates were never influenced by shading from soybeans. This was true since the leaf sampled, that subtending the ear, was always above the soybean canopy. Therefore, the incident light regime of the photosynthetic samples of both monoculture and polyculture were similar. This suggested that other factors such as water and nutrients might be limiting. This limitation of water and nutrients would supposedly originate due to the presence of the soybeans. The fact that corn AP rates increased (significant between .10 and .05) as the distance between corn and soybean rows decreased (Figure 25), suggested that the source of competition might be subterranean, since the intimacy of the root systems decreased from spatial levels one to three. Polyculture corn yields followed very closely the AP rate pattern over the three soybean spatial levels (Figure 6 and 25).

Land Equivalent Ratio

The LER's which were judged significantly different (between .10 and .05), those involving the soybean spatial levels, and also the interaction of corn population and soybean spatial level, generally were consonant with the collective behavior of the observed LAI's and AP rates. As reported earlier, results of the interaction of population and spatial arrangement showed that LER increased steadily from

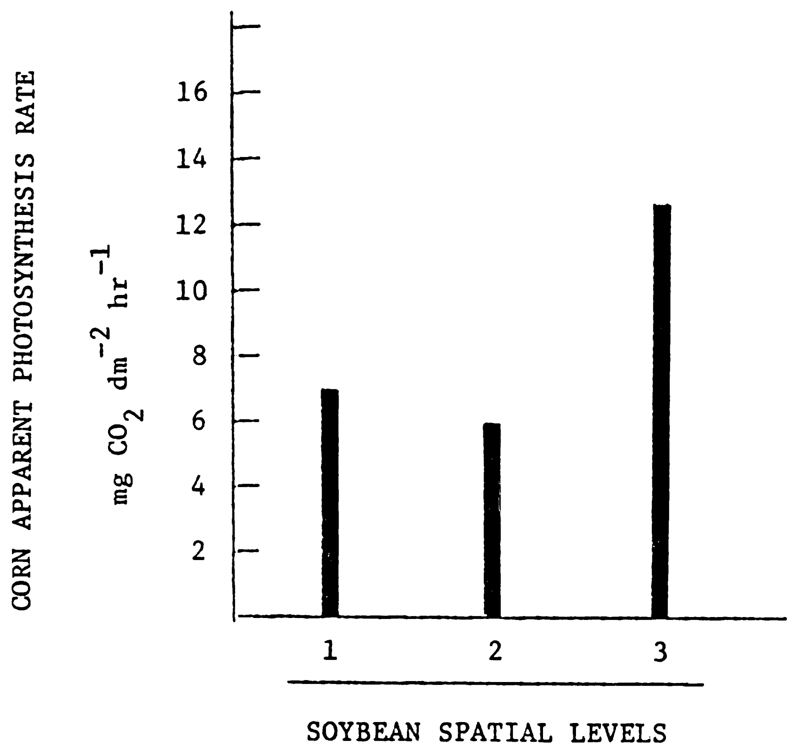

FIGURE 25. Effects of soybean spatial arrangement on the apparent photosynthesis rates of corn.

spatial levels one to three under high corn population, while under low corn population there was a trough effect with spatial levels one and three at the upper edges and spatial level two at the bottom (Figure 8). The results of the high corn population portion of the interaction were explained by the significantly larger corn AP rates and LAI's in the third spatial level than in the first and second spatial levels. Coupled with this was a significantly smaller AP rate for soybeans under high corn population, and a larger amount of inter-specific competition in spatial levels one and two. The combination of all these factors, corn AP and LAI, soybean AP and LAI, and the increase in inter-specific competition, resulted in the development of a more favorable environment for corn as the distance between corn and soybeans increased. The percentage of the LER contributed by corn increased from spatial levels one to three, while soybeans' contribution remained constant. The increase in corn's contribution followed exactly the increase in LER.

Whereas the corn yield was the primary determinant for the size of the LER's under high corn populations, both corn and soybean yields were important to LER's under low corn population, but their relative importance was dependent upon the soybean spatial level. In the first spatial level, corn LAI's were significantly lower than in the third spatial level, while soybean LAI's in the first spatial levels were generally large. Soybeans' LAI's (Figure 20) in the first spatial level of the 100 and 130 cm row widths were larger than for spatial levels two and three. In the 75 cm row width soybean LAI for the first spatial level LAI was lower than for spatial levels two and three, but it still was equal to or larger than any of the LAI's in the other two row widths. The combination of the significantly lower corn LAI's and the relatively large soybean LAI's in all of the first spatial levels was presumedly responsible for the greater contribution soybean yields made to the system LER (approaching 50%) in spatial level one compared to the soybean's contribution in spatial levels two or three.

The reverse occurred in the third spatial level, as significantly larger corn LAI's intercepted more light, increasing corn yields and reducing the yields of the soybeans. Also, the significant increase in corn's AP rate contributed to the diminished importance of soybeans and to the larger contribution corn yield made to the system than in the first spatial level.

Discussion

The differences in final corn yields are quite accurately described by the observed corn AP rates and corn LAI measurements. As would be expected the high corn populations (averaged over spatial levels and corn row widths), with their larger LAI's (2.66), yielded significantly more than the low population corn, which had significantly smaller LAI's than high population corn. Final corn yields were also significantly influenced by the soybean spatial arrangement. Changes in corn yields were apparently caused by changes in corn LAI's as well as a change in its AP rate. Corn associated with soybeans in the third spatial level had the largest values for both LAI and AP.

Where intra-specific corn competition was greatest, under high population conditions, the effects were so complete that soybean yields were uniformly low and not significantly different. However, the effects of soybean spatial level on corn yields illustrated that even though soybean yields were uniformly reduced, inter-specific competition was acute enough to significantly reduce the corn's LAI and AP rates in the second and third spatial levels. This ultimately caused a decrease in corn yields for these spatial levels. The degree of inter-specific competition caused by the soybeans seemed partially due to the soybean's adaptability. It is especially interesting to note that the soybean LAI's were not significantly influenced by the corn population, even though soybean plants in the low corn populations had significantly more leaves, 15.0 and 17.4 leaves per-plant for high and low corn population, respectively. It must be assumed that the leaf blades expanded under the shading of high corn populations to facilitate the capture of the greatly reduced light.

The yield of polyculture soybeans was significantly influenced by the combination of corn population, corn row width, and soybean spatial arrangement. In spite of the significant (.05) influence of the three-factor interaction, it is important to note that the final total polyculture system yields were predominantly influenced by corn population and corn row width (Table A2). Using the calculated LSD, it was shown that there were no significant differences between polyculture soybean yields within the high corn population treatments, but differences were present within the low corn population (Figure 7). It is clearly evident that the soybean yield increases between the high and low corn populations were more pronounced in the 75 cm row width than in either the 100 or the 130 cm row widths. Also, soybean yields in all spatial levels in the 75 cm row width increased, whereas

only the first spatial level increased significantly in the 100 and 130 cm row widths when corn population was decreased.

Most of the variability in the final soybean yields can be explained by the doubling in soybean AP rate between high and low corn populations and the significant difference in corn's and soybean's LAI's within the three row widths (Figure 23 and 26). The most obvious result of the reduction in corn population, was an increase in the amount of incident light available to the soybeans. This was reflected in the change in soybean AP rates between high and low corn populations, almost doubling from 6.7 to 12.6 mg $CO_2 dm^{-2} hr^{-1}$, respectively. A more subtle AP rate change occurred due to the combination of corn population and soybean spatial arrangement. It was concluded that these data were too variable, due to the limited number of samples per mean, to be representative.

The development of the soybean canopy was related to the availability of light, which in turn was related to the size and distribution of the corn's LAI. Lower amounts of light results in larger soybean LAI's. Figure 15 shows that under low corn population, treatments in the 75 cm row width had 30% of the total sunlight at the 85 cm height in the canopy. This compared to 35 and 49% of total sunlight for the same height in the 100 and 130 cm row widths, respectively. The corn LAI's were greatest in the 130 cm row width at 2.47, followed by the 75 and 100 cm row widths with LAI's of 2.23 and 1.97, respectively (Figure 18). The size of the soybean LAI was inversely related to the amount of available light in the three row widths, 3.30, 2.90, and 2.50 LAI in the 75, 100, and 130 cm row widths, respectively. While the 75 cm row width had the highest soybean LAI,

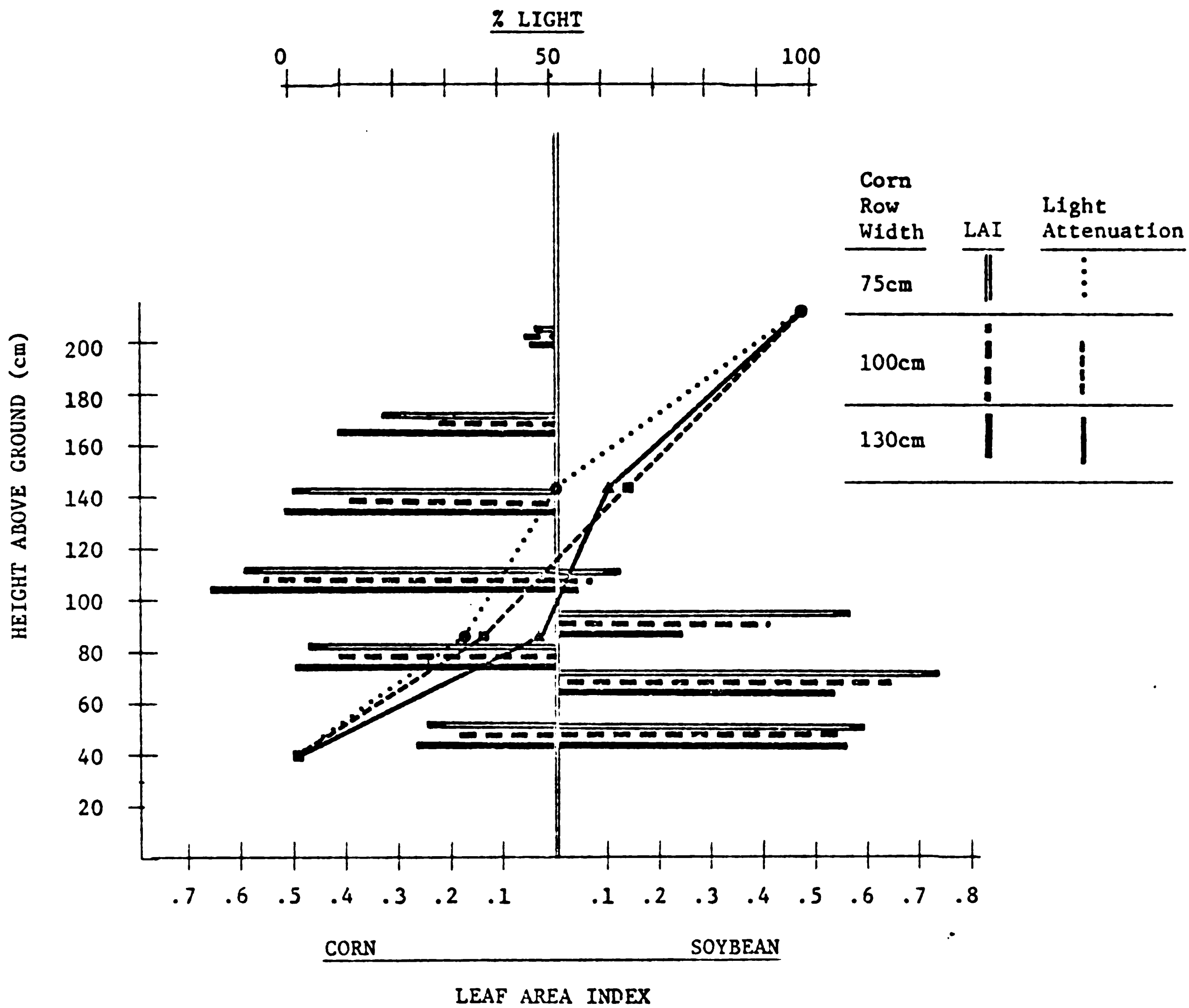

FIGURE 26. Effects of corn row width (averaged over corn population and soybean spatial arrangement) on the size and distribution of the LAI's of corn and soybeans and on the attenuation of light through the polyculture canopy.

it also had significantly different vertical distribution of soybean leaf areas than did the other two row widths, as shown in Figure 26. The soybean plants in the 75 cm row width had significantly larger LAI's at the 90 and 70 cm height above ground strata than did soybean plants in the 100 and 130 cm row widths at those heights. It is interesting to note that the corn LAI's in the 130 and 75 cm row widths, while similar in size and distribution, resulted in a very different affect on light attenuation and hence soybean LAI in those row widths. This would suggest that the polyculture soybean yield was governed by both the magnitude and vertical distribution of the soybean LAI's, which were in turn dependent upon the corn row width.

SUMMARY AND CONCLUSIONS

A corn and soybean polyculture experiment was conducted in 1978 at the Crop Science Research Farm at Michigan State University, in E. Lansing, Michigan. In this experiment, 18 different polyculture treatments, arranged in a 2 x 3 x 3 factorial design, were examined. Independent variables were corn population, high and low; corn row width, 75, 100, 130 cm; and soybean spatial arrangement, minimum, medium, and maximum distance between corn and soybean rows. The parameters measured for both soybeans and corn were: number of leaves per-plant, leaf area index, apparent photosynthesis, components of yield, final yield, and light attenuation through the polyculture canopy. An analysis of these parameters centered on their relationship to changes in inter- and intra-specific competition. Conclusions from this study were:

1. To achieve the highest system productivity under high levels of corn intra-specific competition, the level of inter-specific competition should be as low as feasibly possible within the polyculture framework.

2. At low levels of corn intra-specific competition (low corn population) the intimacy of row arrangement between corn and soybeans will determine which crop has the competition advantage. Under the most intimate row arrangement, soybean yields comprised a larger portion of the system LER than under less intimate conditions. Under

the least intimate arrangement, soybean yields declined and corn yields increased relative to the most intimate spatial level. The LER's in these two row intimacy conditions were nearly equal. In practice this would be an important consideration, since it would provide the farmer with a mechanism to control the relative quantity of corn and soybeans in the final yield. With such flexibility, the farmer could respond to the market price difference between the two crops or to basic nutritional considerations.

3. The distance between corn rows did not influence the corn yield, but it did influence the soybean LAI and ultimately the soybean yield. Soybean LAI's were significantly greater in all 75 cm row width spatial levels, which partially explained the significantly higher soybean yields in the 75 cm corn rows. The effects of corn row widths were important only in conjunction with corn population and soybean spatial arrangement.

4. The soybean spatial arrangement did influence corn yields. Corn yields were significantly smaller in the most intimate corn/ soybean arrangement than in the other spatial arrangement. The reduction in corn's AP rate and LAI in the most intimate spatial arrangement was clearly manifested in corn yields. The cause of the reduction in corn's AP rate was thought to be subterranean competition between corn and soybeans root systems for growth factors.

5. Soybean plant response to different spatial arrangements did influence the soybean's final yields and the proportion of it in the system LER. These significant yield responses were generally confined to the 75 cm row width and to low corn populations.

6. Although there was not a strong statistical mandate

(significant differences between .10 and .05), it appears that polyculture LER's may have been higher in the third soybean spatial level. This was consistently true under high corn populations, but less so under low corn populations. Under low corn populations, soybean yields played a large role in determining the productivity of the system.

7. This study showed that there was generally no total grain productivity advantage or disadvantage from growing these two crops in polycultures at this location.

APPENDIX

Table A1.

CROP SCIENCE FIELD LAB RAINFALL
MT. HOPE AND BEAUMONT

INCHES RAIN PER MONTH

YEAR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	TOTAL
1978	1.81	2.74	2.83	1.73	3.17	4.38	2.68	19.34
17 year AVERAGE	3.07	2.72	4.15	2.88	2.92	3.16	1.85	20.75

Compiled by Dr. M.B. Tesar

Table A2.

ANALYSIS OF VARIANCE FOR GRAIN YIELD OF SOYBEANS GROWN IN POLYCULTURES

SOURCE OF VAR.	df	MS	F-test
Block	2	64964.5	ns.
Corn Pop.	1	1900613.0	***
Corn Row Width	2	305580.0	***
Pop X Row Width	2	121174.2	ns.
Soybean Spatial Arrg'mt	2	160302.6	**
Pop X Spatial Arrg'mt	2	81445.3	ns.
Width X Spatial Arrg'mt	4	5783.6	ns.
Pop X Width X Spatial	4	75311.7	*
ERROR	34	27766.6	
TOTAL	53		

Analysis of variance for soybean yield per hectare in the polyculture cropping system. (*,**, and *** represent significance at the .05, .01, and .001 levels, respectively).

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