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Modeling Light Interception and Distribution in Mixed Canopy of Redroot Pigweed (*Amaranthus retroflexus*) in Competition with Corn (*Zea mays*)

Farshid VAZIN, Ahad MADANI, Mojtaba HASSANZADEH

Islamic Azad University, Gonabad Branch, Gonabad, Iran; Farshidvazin@gmail.com

Abstract

To model light interception and distribution in the mixed canopy of redroot pigweed (*Amaranthus retroflexus*) with corn, an experiment was carried out in randomized complete blocks design with factorial arrangement in Gonabad during 2006-2007 and 2007-2008 growing seasons. The factors used in this experiment was consisted of three corn densities (7.5, 8.5 and 9.5 plants per meter of row) and three densities of redroot pigweed (zero, 2, 4, 6 and 8 plants per meter of row). INTERCOM model was used through replacing parabolic function with triangular function of leaf area density. Vertical distribution of the species' leaf area showed that corn had concentrated the most leaf area in layer of 50 to 150 cm, while redroot pigweed has concentrated in 40-60 cm of canopy height. Model sensitivity analysis showed that leaf area index, species' height, height where maximum leaf area is seen (hm), and extinction coefficient had influenced on light interception rate of any species. In both species, the distribution density of leaf area at the canopy length fit a triangular function, and the height in which maximum leaf area was observed change by increasing the density. There was a correlation between percentage of the radiation absorbed by the weed and percentage of corn seed yield loss (r^2 = 0.89; P<0.01). Ideal type of corn was determined until the stage of tasseling in competition with weed. This determination indicates that the corn needs more height and leaf area, as well as less extinction coefficient to successfully fight against the weed.

Keywords: modeling, competition, redroot pigweed, corn, light

Introduction

Light plays the most important role among all environmental factors affecting competition in mixed canopy (Keating and Carberry, 1983). Most of differences observed in the yield of competing species in mixed culture are due to differences in the amount of light received and/or its consumption efficiency (Sinoquet *et al.*, 1996). Canopy structure is one of the most important factors in determining the competitive ability of crop and weed (Caldwell, 1987). The plant structure that is suitable for pure culture is not necessarily suitable for mixed culture. For example, it is an advantage for a species in mixed culture, to have more leaf area index or more horizontal leaves above the canopy; but it is not necessarily an advantage in pure culture (Rhodes and Stern, 1978). Leaf angle, leaf area index, and leaf area distribution are traits with major role in light interception and consequently canopy photosynthesis (Anten and Hirose, 1999; Hirose *et al.*, 1997; Vazin *et al.*, 2010). However, those traits that lead to maximum canopy photosynthesis are not necessarily seen in each single plant. For example, photosynthetic capacity of canopy with vertical leaves is higher than horizontal leaves because more light will pass among the vertical leaves, reach lower layers, and lead to uniform distribution of light within the canopy. However, a crop with horizontal leaves will receive more light and have more photosynthesis when weeds have vertical leaves (Toller and Guice, 1996). It is impossible to measure light interception by each species in the mixed canopy. So modeling of light interception process is considered as the most favorable method to determine the light received by any species (Berkowitz, 1988). In the past decades, several models have been proposed to predict the competition for light. Photosynthetic models express how light interception and consumption is done by the different species in the canopy (Hikosaka *et al.*, 1999). Spitters and Aerts (1983) proposed a model in which the canopy was divided into several layers, and light interception of each layer was calculated based on the contribution of leaf area to this layer. It is impossible to use light interception models in mixed canopy without describing the canopy structure and its effect on light interception by different species (Toller and Guice, 1996). To test this hypothesis and simulate the light received by species of broadleaf weed of redroot pigweed (*Amaranthus retroflexus*), this study was performed in competition with corn in order to determine the amount of light received as well as the affecting factors.

Materials and methods

Field experiments

The experiment was performed in the 2005-2006 and 2006-2007 growing seasons of in the research farm of

Islamic Azad University (Gonabad branch). The site is located at 34°21′ North latitude, 58°41′ East longitude, with an altitude of 1056 m above the sea level, in a land with loamy clay soil. The average annual rainfall is 142 mm in the region, and the annual absolute maximum and minimum temperatures are reported to be 24.1 and 10.8 °C, respectively. The weather of this region has been determined cold and dry based on Emberger climate. The experiment was performed as factorial based on randomized complete blocks with three replications. In the first experiment, experiment factors were consisted of : corn density in three levels (7.5, 8.5, 9.5 plants per meter of row) and redroot pigweed density in five levels (zero, 2, 4, 6 and 8 plants per meter of row). The corn genotype used in both experiments was SC704. The experiment was carried out in an incremental method in which the corn density was fixed in each level while redroot pigweed density was variable. Urea and ammonium phosphate fertilizer were used with rate of 150 (69 kg nitrogen) and 180 (4.86 kg nitrogen) kg per hectare, respectively. Ammonium phosphate fertilizer was mixed with the soil before planting, and urea fertilizer was used two times (50% at planting and 50% at emergence of male inflorescence). Plot size of 5 x 6 meter, having 6 rows and 0.75 m row spacing was used. Before planting, the corn seeds were disinfected by using vitavax fungicide. In May 5th, planting was manually done when soil water content reached 75% of available amount. Planting depth was 5 to 6 cm. Two to three seeds were planted at each interval based on the densities intended in project and thinned to one after seedling emergence (trifoliate stage). Furthermore, weed seeds were uniformly planted based on the intended density between the corn's rows. The first furrow irrigation was done in May 15th. The next irrigation took place as normal routine based on plant need and common irrigation cycle in the area where the experiment is located. Additional redroot pigweed seedlings were removed by hand in order to obtain the desired densities. Undesired weeds were controlled by pulling and hoeing at frequent intervals. From three-leaf stage of corn to physiological maturity, sampling was done once every two weeks. In each sampling, plants were taken out with roots, and their height was measured after washing out the roots. Then plant leaves were separated, LAI were determined by leaf area meter device (LI-COR Model LI-3000A Portable). In the 84th and 98th days after planting, the vertical distribution of the species' leaf area was measured by measuring leaf area index in 9 layers of 20 cm (0-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, 140-160, 160-180 cm from soil level). For this reason, the plants in each sample were divided into 20 cm layers, and the leaves in each layer were separated. Then the areas of leaves were determined. All plants samples were taken from 30 cm of the inner for rows. To study the distribution of light in the canopy (120 days after planting), the radiation measuring device (SunScan model SS1-R3-BF3) was placed on a metal base having a movable adjustable clamp, and then the amount of light was measured in the top and bottom of each layer. Corn was hand-harvested from 2 m of the inner four rows to determine the grain yield. To measure the total biomass, samples were dried in oven with a temperature of 70 °C for 48 hr. For testing the validity and sensitivity of the model, t-student and chi square test were employed using Sigmaplot and SAS softwares. Drawings of diagrams were done by Excel or Quattroporo.

Model structure

Within a canopy, radiation from the top to bottom is exponentially reduced based on the following equation:

$$I_h = (1 - p)I_0 exp(-KL) \qquad \text{Equation (1)}$$

Where:

I_h= amount of radiation in canopy's height h, in terms of joules per square meter of land per seconds;

I_0= amount of radiation above the canopy (joules per square meters of land per second);

L= cumulative leaf area index from top to bottom of canopy (square meter of leaf per square meter of land);

P= reflection coefficient of light in canopy;

K= light extinction coefficient (square meter of the land per square meter of leaf).

Coefficients of reflection in canopy are calculated based on diffusion factor of single leaves as follows (Nassiri and Elgersma, 1998):

$$P = \left[\frac{\left(1 - \sqrt{(1-\sigma)}\right)}{\left(1 + \sqrt{(1-\sigma)}\right)}\right] * \left[\frac{2}{1 + 1.6\ sin\beta}\right] \text{Equation (2)}$$

Where:

σ= diffusion coefficient of single leaves for visible radiation, whose amount for most agricultural species is nearly 0.2;

ß= height of the solar.

Although Equation (1) is suitable for pure culture, the cumulative leaf area of any species above a specified height should be separately calculated in mixed cultures where there is more than one competing species and where species have different heights.

In this case, equation (1) will be as follows:

$$I_h = (1 - p)I_0 exp(-\sum K_i L_{h,i}) \qquad \text{Equation (3)}$$

Where:

I_h= radiation in height (joules per square meter per second);

I_0= radiation above the canopy (joules per square meter of land per second);

$L_{h,i}$= cumulative leaf area index (toward bottom) of species i in each height of the canopy;

K_i= extinction coefficient of species i (square meters of land per square meter of leaves).

Cumulative leaf area is calculated based on the relationship between leaf area density and plant height. Leaf area density or LAD shows the leaf area around a particular point from canopy height (square meter of leaf per land's square meter per height).

LAD is used in different models to calculate profile and light interception in mixed species (Kropff *et al.*, 1993). Different functions are considered in different models for the leaf canopy distribution. Kropff *et al.* (1993) considered leaf area distribution in the canopy as a parabola in INTERCOM model. In the parabolic function, it is assumed that the maximum leaf area of any species can be obtained in 50 percent of height. In mixed culture of most species, there is no parabolic distribution of leaf area. For example, in mixed culture of clover with grass, the clover has more leaf area density (LAD) at the upper section of the canopy (Nassiri and Elgersma, 1998). The results of this experiment also suggested that there is more leaf area in upper canopy layers of redroot pigweed, compared to corn. Therefore, leaf area distribution is not in a parabolic form, which is the reason why triangular function, as follows, was used instead of parabolic LAD function in this experiment (Nassiri and Elgersma, 1998):

$$LAD_h = L_{d,m}\frac{(H-h)}{(H-h_m)} \quad h_m \le h \le H \qquad \text{Equation (4)}$$

$$LAD,_h = L_{d,m}\frac{h}{h_m} \quad 0 \le h \le h_m \qquad \text{Equation (5)}$$

Where:

LAD_h= leaf area density at the intended height (m^2 m-3);

$LAD,_h$= maximum leaf area density of the leaf (LAD_{max})

h_m= height where maximum leaf area density can be seen (cm);

H = total canopy height.

The following relationship can be used:

$$L_{d,m} = \frac{2LAI}{H} \qquad \text{Equation (6)}$$

After calculating the LAD based on the above relationships, the cumulative leaf area index (toward bottom) of each species *i* in each canopy height can be calculated as follows:

$$L_{h,i} = \left[\frac{\left[1-\left[\frac{h_i}{H_i}\right]\right]}{1-\left[\frac{h_{m,i}}{H_i}\right]}\right]L_i \quad h_{m,i} \le h_i \le H_i \qquad \text{Equation (7)I}$$

$$L_{h,i} = \left[1-\frac{h_i}{H_i * h_{m,i}}\right]L_i \quad 0 \le h_i \le k_{m,i} \qquad \text{Equation (7)}$$

$L_{h,i}$= cumulative leaf area index of species *i* at height *H*

L_i= leaf area index of the whole species *i*;

h_i= intended height in the canopy;

H= height of whole species *i*;

h_m= height where maximum LAD has been seen.

After placing cumulative leaf area index ($L_{h,i}$) in equation 3, the amount of PAR radiation can be calculated at each height in the mixed canopy.

Results and discussion

Validation of model

Vertical distribution of leaf area

To test the validity of the model, data collected from the experiment were noted and compared with the data provided by the model. The results suggested that the triangular function of leaf area density was appropriate for the studied species, and has provided a suitable prediction of real data (Fig. 1). Corn LADm was shown to be bigger than redroot pigweed LADm, indicating that there is more competitive power in corn, compared to redroot pigweed (Fig. 1). Maximum LAD of corn in competition with that of redroot pigweed was seen at the height of 85 cm (48 percent of total height). Maximum LAD of redroot pigweed was seen at the height of 46 cm (44 percent of total height) (Fig. 1). Comparison of LAD values in different density showed that the height where maximum LAD can be observed is affected by the density, and its amount will be increased with the increase in density of corn (Fig. 1). Also, it seems that with increase in density, competition for light will be increased and that the height not only will be affected, but also will the distribution pattern of the leaf canopy. Height and leaf area index are regarded as two factors determining competitive advantage in crop-weed mixed canopy. It is believed that the species with more leaf area and height will be more successful (Holt, 1995).

Radiation interception by mixed canopy

In addition to leaf area, the radiation absorbed by the mixed canopy was also used to validate the model. For this reason, the radiation absorbed by mixed canopy was simulated for any density of corn, which highest density in the experiment was used for weed. Then, the actual measured values of radiation were compared with the values predicted by the model, whose results suggested that in all cases, an appropriate model of estimation is provided from the actual data (Fig. 2). In this model, extinction coefficient was considered to be constant. Extinction coefficient is equal to 0.65 for corn and 0.7 for redroot pigweed (these values were calculated through parameter model to

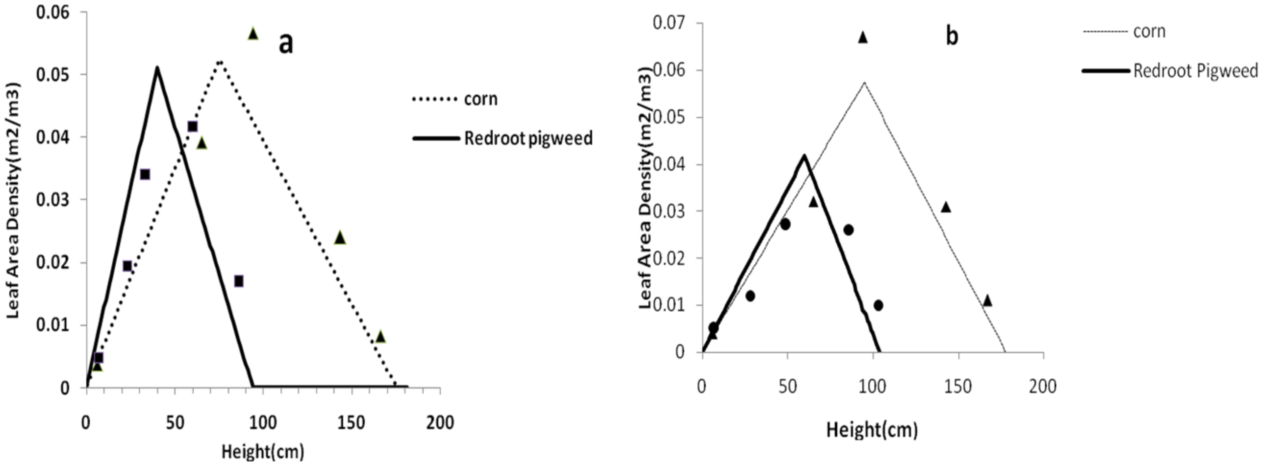

Fig. 1. Vertical distribution of corn and redroot pigweed leaf area at 90 days after planting at densities of corn of 7.5 (a) and 9.5 (b) plants per meter of row. and the highest density of redroot pigweed (8 plants per meter of row)

achieve best compliance with experimental data at a constant density, and then were used in other cases). Depreciation coefficient of vertical leaf species (monocotyledonous) was reported to be between 0.4-0.7 and horizontal leaf species (dicotyledonous) to be between 0.65-1 (Monteith, 1969).

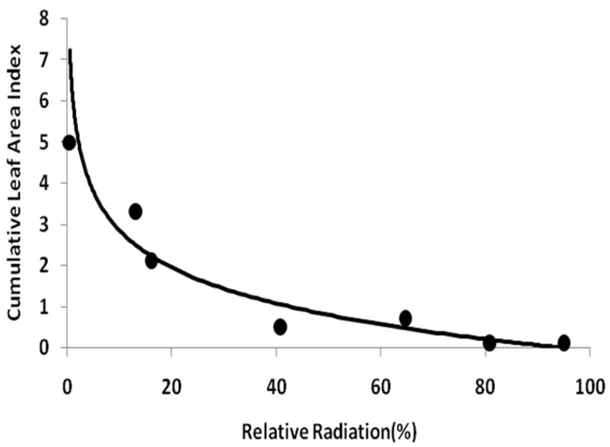

Fig. 2. Light extinction of mixed canopy of corn and redroot pigweed in 90 days after planting at lowest density of corn (7.5 plants per meter of row) and the highest density of redroot pigweed (8 plants per meter of row)

Testing model sensitivity

To evaluate the amount of model sensitivity to each of the parameters affecting it, leaf area index, and the height where maximum leaf area density (hm) is placed, as well as extinction coefficient (K) of any species were changed between 5 and 30 percent. And in any case, the amount of light interception was determined by the model for each species (Tab. 1). In case 1, values of parameters will be the same for both species, and the amount hm was considered in half canopy (parabolic distribution). In this condition, the light absorbed by both species was equal (Tab. 1). Among the parameters studied, the height change showed the biggest effect on light interception, so that the height of corn (species 1) increased by 30 percent compared to case 1, and by 28 percent compared to weed (Tab. 1). It is in the case that 30 percent of increase in leaf area index and hm, and/or of decrease in the extinction coefficient, caused the increases of 15, 15 and 13 in light interception for corn compared to case 1 and increases of 12 percent in light interception compared to weed (Tab. 1). So, any species with more height and less depreciation coefficient or with more leaf area density in upper canopy layers will be able to intercept more light and to have higher competition ability.

Determination of the ideal type of corn in competition with weed for light

Model sensitivity test showed that height, leaf area index, the height where the maximum leaf area index can be seen (hm) and extinction coefficient of species are important in light interception (Tab. 1). For this reason, these treats were used when designing the ideal type of corn. Considering that the agricultural crop yield rate is a function of the light received and of light consumption efficiency, it can be said that those species that receive a greater share of light would have a higher grain yield. The amount of light received for use in designing the ideal type of corn depends on the plant density. Considering that the results suggested that the highest grain yield of corn is achieved in density of 9.5 plants per meter of row (data not shown), the amount of the light received by the corn in pure culture was considered as basis in the density above. However, corn was approximately two times higher than redroot pigweed in the intended density (Fig. 3), as well as receiving more light (nearly 3 times), the ideal type of corn was designed in competition with two weeds for receiving light until the time of tasseling (70 days after planting). Real values relating to parameters of height, leaf area index, the height where maximum LAD has been

Tab. 1. Results of model sensitivity test in different conditions and the percentage of light absorbed by each species

Cases / Parameters	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
LAI1	3.5	3.67	3.82	4.02	4.2	4.37	4.55	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
LAI2	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
H1	130	130	130	130	130	130	130	136	143	149	156	162	169	130	130	130	130	130	130	130	130	130	130	130	130
H2	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
Hm1	65	65	65	65	65	65	65	65	65	65	65	65	65	68	71	75	78	81	85	65	65	65	65	65	65
Hm2	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
K1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.73	0.77	0.81	0.84	0.88	0.91
K2	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
PAR1	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.50	0.53	0.55	0.57	0.59	0.61	0.48	0.49	0.50	0.51	0.52	0.54	0.46	0.45	0.44	0.43	0.42	0.41
PAR2	0.47	0.46	0.45	0.44	0.43	0.42	0.41	0.44	0.41	0.39	0.37	0.34	0.33	0.46	0.45	0.44	0.43	0.42	0.41	0.48	0.49	0.50	0.52	0.53	0.53

LAI=leaf area index; Hm = height where maximum density of leaf area is seen; H= height; K= extinction coefficient; PAR = ratio of absorbed radiation; Note: (1) and (2) legends are related to corn and redroot pigweed, respectively

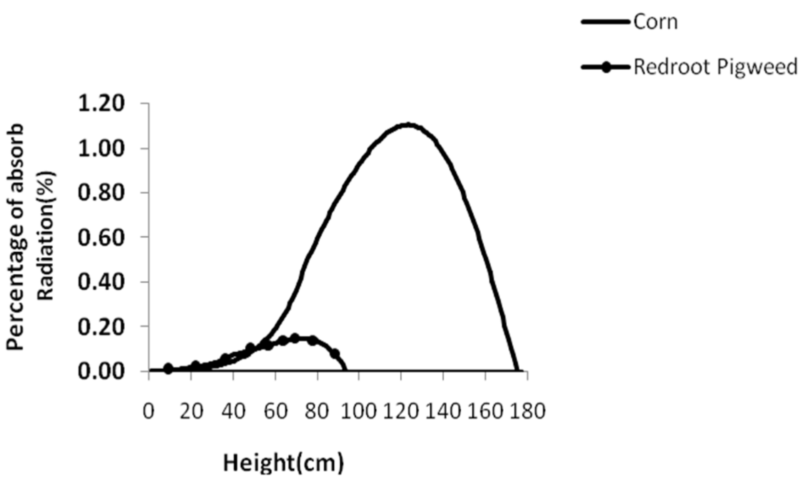

Fig. 3. Percentage of the absorbed radiation per centimeter of the canopy height in lowest densities of corn at the highest density of redroot pigweed

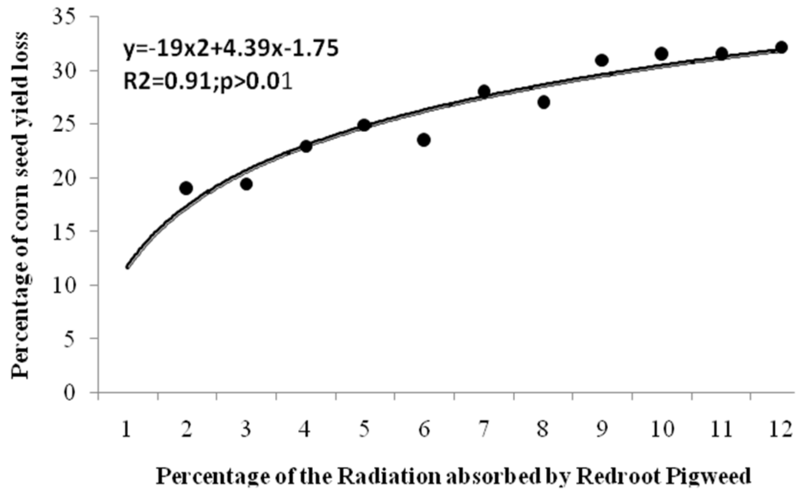

Fig. 4. Relationship between the percentage of radiation absorbed by the weed and the percentage of corn seed yield loss

Tab. 2. Comparison of the parameters used in model in normal case with the ideal types of corn in competition with redroot pigweed

Parameters	Case 1	Case 2	Case 3
LAI1	2.72	3.5	3.5
LAI2	2.13	2.13	2.13
H1	95	100	103
H2	95	95	95
Hm1	87	90	85
Hm2	64	64	64
K1	0.65	0.5	0.5
K2	0.7	0.7	0.7
PAR1	0.62	0.74	0.74
PAR2	0.30	0.17	0.18

Case 1: real cases of corn in density of 9.5 plants and weed at highest density (8 plants per meter of row); and Cases 2 and 3: ideal types of corn; LAI1 and LAI2 are leaf area indexes of corn and weed, respectively; and H1 and H2 are heights of corn and weed; Hm1 and Hm2 are corn and weed heights where there are maximum leaf area indexes, respectively for corn and weed; K1 and K2 are extinction coefficients of corn and weed, respectively; PAR1 and PAR2 are ratio of absorbed radiation for species 1 (corn) and 2 (redroot pigweed)

seen (hm) and the extinction coefficient obtained from experiments were placed in the mentioned density of the model, and the amount of light received in this case was computed by the model. Then, with the assumption that the ideal type of corn should intercept at least 80 percent of light absorbed in pure culture, in competition with the weeds, the ideal corn type was designed. In the experiment that is performed for the purpose of comparing competition of broadleaf weeds and grasses with corn, it was specified that 76 percent of the corn's leaf area and only 23 percent of the weeds' biomass have been placed above a meter over the surface of the soil. In these circumstances, the competition of weed for interception of the light that reached the canopy was weak, because about 75 percent of the input radiation is absorbed by the upper layer of corn coverage. However, even if competition for light interception is relatively weak, the same small amount of light passed through corn canopy is sufficient for weed growth and competition will be continued through interference for exploiting other resources (Tollenar, 1994).

Real values of the parameters above were used for weed at the highest density (8 plants per meter of row). Then, values of parameters were changed for corn, and the amount of the light absorbed by any species was determined in each case. Countless number of cases were evaluated, among which the cases absorbing 80% of the light (compared to their pure culture, i.e. in a density of 9.5 plants per meter of row) were selected. Then, those cases in which the corn had a desirable limit of the traits above were screened, and were introduced as the ideal type of corn in competition with weed.

Light interception was compared in normal and ideal type corn at the time of tasseling (Tab. 2). This comparison showed that in density of 9.5 corn plants per square meter at the highest density of redroot pigweed (8 plants per meter of row), the contribution of normal type corn and redroot pigweed to the light interception were 0.62 and 0.30, respectively, while these values were 0.74 and 0.17in the ideal type of corn (Tab. 2). Comparison of light interception rate in competition with redroot pigweed shows that ideal type of corn in competition with the normal redroot pigweed has an increase of 0.22 in leaf area index, compared to the normal case (Tab. 2). Overall, it can be said that the biggest difference of the ideal type of corn in competition with redroot pigweed is related to the leaf area index which suggests that the corn needs to maintain leaf area index and increase it at this stage. This can be, to some extent, achieved through applying management practices including increase in the density of agricultural plant, just as the competitive power of the weeds was decreased by increasing the corn density to the rate of 9.5 plants per square meter.

Ranges of height changes in the ideal type of corn were between 5 to 8 percent in competition with redroot pigweed, which it is possible to achieve (Tab. 2). There was a correlation between the percentage of weed-absorbed radiation and the percentage of the corn seed yield loss (Fig. 4).

The percentage of the corn seed yield loss was increased with an increase in the percentage of the radiation absorbed by weed. According to the interception of about 10 percent of radiation by redroot pigweed (Fig. 4), this weed will be followed by maximum corn seed yield loss, so it seems that the factors other than light can cause corn seed yield loss. Comparison of parameter r (Equation 20) about the redroot pigweed showed that the value of this parameter concerning redroot pigweed is equal to 0.35 (difference based on t test was significant at the level of 0.01).

$$YL\% = \frac{YL_{max}}{(1 + b * exp(-r * 1))} \quad \text{Equation (20)}$$

where:

YL= Percentage of corn seed yield loss;

YI_{max}= maximum percentage of yield loss;

I= percentage of the radiation absorbed by the weed;

r= average rate of the corn seed yield loss in reaction to loss of the radiation absorbed by the corn.

Conclusions

The results suggested that the triangular function of leaf area density was appropriate for the corn and redroot pigweed species, and has provided a suitable prediction of real data and corn will be able to preserve their yield as much as acceptable if it can increase its light interception rate to 80% of pure culture until the stage of tasseling.

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