Growth Analysis of Tomatoes in Black Polyethylene and Hairy Vetch Production Systems

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Additional index words. *Lycopersicon esculentum*, *Vicia villosa*, cover crop, mulch, leaf area

Abstract. Growth analysis was used to document growth responses of staked, fresh-market tomatoes (*Lycopersicon esculentum* Mill.) to black polyethylene or hairy vetch (*Vicia villosa* Roth) mulches. Leaf area and dry mass of vegetation and fruit were measured weekly during two growing seasons. Growth was better early in the season but worse later in the season for plants grown with black polyethylene than with hairy vetch mulch. Unit leaf rate (rate of growth per unit leaf area) of fruit was higher with black polyethylene than with hairy vetch, whereas the reverse was true of vegetation. This relationship led to a higher leaf area ratio and leaf area duration of plants grown with hairy vetch than with black polyethylene. Consequently, tomatoes grown with black polyethylene produced higher early yield because of increased partitioning to fruit. However, tomatoes grown with hairy vetch eventually outgrew and outyielded those grown with black polyethylene because of increased partitioning to leaf area.

Researchers have investigated tomato production from transplants in organic and/or cover crop mulches with variable results. Conventional tillage improved tomato yield compared to various no-tillage cover crop systems in Alabama (Doss et al., 1981), Ohio (Creamer et al., 1996), and Illinois (Mwaja et al., 1996), but Shelby et al. (1988), in Tennessee, found higher yields in a no-tillage system with wheat (*Triticum aestivum* L.) residue than in a conventional-tillage system. Organic mulches have provided increased (Tindall et al., 1991), equivalent (Steffen et al., 1995), and decreased (Chakraborty and Sadhu, 1994) tomato yields compared to black polyethylene mulch. Hairy vetch was not included or was included only in mixtures in most of these reports.

Hairy vetch has proven to be a profitable cover crop for fresh-market tomato production. Yields of tomatoes grown with a hairy vetch cover crop were higher and costs were lower than those of tomatoes grown with black polyethylene mulch or bare soil (Kelly et al., 1995). Regardless of environmental conditions, hairy vetch has provided optimum yields more consistently than other mulches (Abdul-Baki et al., 1996). This cover crop system consists of planting hairy vetch on beds in the

fall and mowing the vetch just before transplanting tomatoes the following spring (Abdul-Baki and Teasdale, 1994). Tomatoes are transplanted with minimal disruption to the mulch, staked, and irrigated through trickle tubes laid on the surface of the vetch residue.

Black polyethylene provides higher soil temperatures in spring than a hairy vetch mulch (Teasdale and Abdul-Baki, 1995). As a result, tomato root and foliage growth early in the season is better when grown with a black polyethylene than hairy vetch mulch. However, tomatoes grown with hairy vetch consistently become more vigorous and outyield those grown with black polyethylene by the end of the season (Abdul-Baki et al., 1996). Our research was undertaken to document differences in tomato growth during this transition to superior growth with vetch than polyethylene mulch. Growth analysis (Causton and Venus, 1981; Hunt, 1990) was used to demonstrate changes in vegetative and reproductive growth rates.

Materials and Methods

Comparisons of tomato growth in the hairy vetch and black polyethylene mulching systems were conducted during 1993 and 1994 in conjunction with experiments described by Abdul-Baki et al. (1996). Fields consisting of a Keyport fine sandy loam (Aquic Hapludults, clayey, mixed, mesic) were located on the Beltsville Agricultural Research Center, Beltsville, Md. Each field was split into two replications with four 31-m rows of each treatment in each replication in 1993 and four 61-

m rows of each treatment in each replication in 1994. Half of each row was used for collecting yield data previously reported (Abdul-Baki et al., 1996) and the other half was used for growth analysis. Experimental units in the growth analysis sections consisted of plants randomly selected from among the four rows as described below.

Beds 15 cm high, 0.9 m wide, and 1.5 m center-to-center were prepared in mid-September of the year preceding the tomato season. Hairy vetch seed was inoculated with the appropriate *Rhizobium* strain and planted at 45 kg-ha⁻¹ with a Brillion seeder (Brillion Iron Works, Brillion, Wis.) running over the surface of the beds. A uniform mat of vetch vines covered the beds and troughs by the following spring. The hairy vetch vines were flail mowed 1 d before transplanting, leaving a finely chopped layer of residue that dried within a few days. The resulting mulch was ≈5 cm thick and had a dry mass of 4360 and 5178 kg-ha⁻¹ and N content of 167 and 197 kg-ha⁻¹ in 1993 and 1994, respectively.

Beds for the black polyethylene treatment were prepared in the spring, before transplanting. One trickle irrigation line (Turbo Tape; Zimmerman Irrigation, Mifflingburg, Pa.) was buried 5 cm below the surface of each bed and 8 cm west of the tomato rows. A nondegradable, black-embossed polyethylene film 1.2 m wide and 0.025 mm thick (Leco Industries, Montreal) was laid mechanically.

Five-week-old 'Sunbeam' tomato plants were transplanted in the center of beds on 11 May 1993 and 16 May 1994 with a no-tillage transplanter (Holland Co., Holland, Mich.) that inserted the plants with minimum disruption into the mulches at a spacing of 50 cm within the row. Drip irrigation lines were secured with U-shaped wires on the surface of the hairy vetch mulch 8 cm west of the tomato rows. Stakes were inserted between every other plant and plants were supported with three tiers of string woven between stakes. Weeds were controlled successfully with postemergence applications of 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one (metribuzin) at 0.56 kg-ha⁻¹ and 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one (sethoxydim) at 0.2 kg-ha⁻¹. Insects and pathogens were monitored using the integrated pest management program of the Univ. of Maryland. Fields were scouted three times a week and pesticides applied as recommended.

Nitrogen at 112 kg-ha⁻¹ was applied as ammonium nitrate through the trickle irrigation system to the black polyethylene-covered beds in 14 equal weekly applications. The hairy vetch beds received the same number and quantity of irrigations but half the N noted above. Phosphorus and K were omitted in both years because of high soil tests for these nutrients.

Tomato plants were sampled weekly from 4 to 17 weeks after transplanting. One plant per replication per week was sampled in 1993 by cutting at the soil surface. Two plants per replication per week were cut in 1994 until week 10, followed by one plant per replication

Received for publication 2 Oct. 1996. Accepted for publication 22 Jan. 1997. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

at later dates. Plants designated for sampling were identified at the beginning of the experiment. Chosen plants were surrounded by at least one unsampled plant on each side and were not visibly different from typical plants in that treatment. Sampled plants were transported in large plastic bags to prevent wilting and processed within 4 h of cutting. Plants were separated into leaves, stems, and green fruit. Green leaf area was measured (LI-3100; LI-COR, Lincoln, Neb.) and green fruit were cut in halves. All parts were held for 14 d in a forced air dryer at 70 °C for dry mass determination. Vegetative dry mass was determined as the sum of leaf and stem dry masses.

Ripe (pink to firm red) fruit were picked weekly from all remaining plants identified for sampling beginning 10 weeks after transplanting. Because one plant per replication per week was harvested, the number of plants designated for picking declined as sampling progressed until termination of the experiment at 17 weeks after transplanting. Ripe fruit were cut into halves and dried for mass determination as described above. Ripe fruit mass per plant was determined by dividing ripe fruit mass in a given week by the number of plants picked in that week. The cumulative fruit mass up to a given week was determined by summing the weekly ripe fruit masses produced up to that week and adding the green fruit mass of the plant sampled on that week.

Since response patterns of leaf area, vegetative mass, and cumulative fruit mass to mulches were similar in both replications in both years and since the time of initial green and ripe fruit development also was similar in both years, data from both years were combined into one analysis. An analysis of covariance was conducted with year, replication within year, and mulch as class variables and various orders of time as regression variables. Higher order terms were added to the model until the highest order term was no longer significant. Interaction terms between mulch and time were then added until the highest order term was no longer significant. Regressions of leaf area, vegetative mass, and cumulative fruit mass versus time were obtained for each mulch using the SOLUTION option to the MODEL statement of PROC GLM (SAS version 6.10, SAS Institute, Cary, N.C.).

Growth analysis (Causton and Venus, 1981; Hunt, 1990) was performed using the mass and leaf area regression equations from the analysis of covariance to calculate the growth parameters described below. The relative growth rate (RGR) is defined as the rate of mass change per unit of mass: $RGR = [d(\text{mass})/dt]/\text{mass}$.

RGR was calculated for vegetative and cumulative fruit mass separately. Vegetative mass was chosen as the denominator for both calculations because it represented the portion of the plant responsible for producing new growth (Hunt, 1990).

Unit leaf rate (ULR) is defined as the rate of mass change per unit leaf area: $ULR = [d(\text{mass})/dt]/\text{leaf area}$.

ULR has been called the net assimilation rate and represents the net rate of photosyn-

Table 1. Analysis of covariance of tomato leaf area, vegetative mass, and cumulative fruit mass with mulch as the class variable and time as the regression variable.

Source	Probability > F value		
	Leaf area	Vegetative mass	Fruit mass
Mulch	0.0001	0.0001	0.1670
Week	0.0001	0.0001	0.0001
Week × week	0.0001	0.0001	0.0043
Week × week × week	0.0001	0.0075	---
Mulch × week	0.0001	0.0001	0.0285
Mulch × week × week	---	---	0.0064

Fig. 1. Tomato leaf area per plant. Regression equations are $Y = -448 + 155X - 0.118X^2 + 0.0000289X^3$ for plants grown with hairy vetch and $Y = -349 + 140X - 0.118X^2 + 0.0000289X^3$ for plants grown with black polyethylene mulch based on model in Table 1 ($R^2 = 0.73$).

Fig. 2. Tomato vegetative dry mass per plant. Regression equations are $Y = -422 + 132X - 8.04X^2 + 0.180X^3$ for plants grown with hairy vetch and $Y = -321 + 119X - 8.04X^2 + 0.180X^3$ for plants grown with black polyethylene mulch based on model in Table 1 ($R^2 = 0.88$).

thate assimilation per unit leaf area. ULR was calculated for vegetative and cumulative fruit mass separately.

Leaf area ratio (LAR) is defined as the ratio of leaf area to mass: $LAR = \text{leaf area}/\text{mass}$.

LAR was calculated using vegetative mass as the denominator. RGR can be expressed as the product of ULR and LAR and, thereby, can be separated into two components, the rate of

assimilation of photosynthate per unit of leaf area and the amount of leaf area per unit mass.

Leaf area duration (LAD) is defined as the leaf area times the length of time the leaf area is present and is computed as the integral of leaf area with respect to time. The limits of computation were weeks 4 to 17 in our research, because leaf areas before week 4 were relatively minimal and the regression equa-

tions did not provide a realistic fit when extrapolated to times earlier than week 4.

Results and Discussion

Analysis of covariance showed a significant interaction between mulch and time for leaf area, vegetative mass, and cumulative fruit mass (Table 1). This analysis demonstrates that the regression models for these parameters were different for each mulch and, consequently, that the pattern of tomato plant growth with hairy vetch differed from that with black polyethylene mulch.

Leaf area (Fig. 1), vegetative mass (Fig. 2), and cumulative fruit mass (Fig. 3) exhibited a similar pattern of response to black polyethylene and hairy vetch mulch, i.e., tomatoes grew better with black polyethylene than with hairy vetch mulch early in the season but the reverse was true by the end of the season. The difference in response to the two mulching systems was most pronounced for leaf area. Leaf area of tomatoes grown with black polyethylene reached a maximum earlier than that of tomatoes grown with hairy vetch, but then declined continuously through the period of fruit ripening (Fig. 1). Leaf area of tomatoes grown with hairy vetch developed more slowly, but after reaching a maximum about the time fruit began ripening, remained relatively intact through the remainder of the season. As a result, LAD of plants grown with hairy vetch was longer than that of plants grown with black polyethylene. LAD was $2259 \text{ dm}^2 \cdot \text{week}^{-1}$ for the hairy vetch treatment and $1486 \text{ dm}^2 \cdot \text{week}^{-1}$ for the black polyethylene treatment.

RGR of the vegetative and fruit portion of tomato plants declined as the season progressed (Fig. 4). This is a typical response attributed to increasing production of nonphotosynthetic structural tissue as the plant matures (Causton and Venus, 1981). RGR of fruit exceeded that of vegetation after the 9th week of the season with both mulches. ULR of fruit also exceeded that of vegetation by the 9th week of the season and remained relatively constant for the remainder of the season (Fig. 5). These results demonstrate that tomato plants partition a constant rate of photosynthate to fruit at the expense of vegetative growth during the period of fruit ripening.

Tomato plants grown with hairy vetch had a higher ULR for vegetation but a lower ULR for fruit than plants grown with black polyethylene (Fig. 5). This result represents a fundamental difference in the growth of tomatoes in these mulches. Tomatoes in hairy vetch appear to partition more photosynthate to vegetation and less to fruit than those in black polyethylene. Higher partitioning to vegetation probably contributed to the higher LAR of plants grown with hairy vetch than with black polyethylene (Fig. 6). The higher LAR of plants grown in hairy vetch eventually offset the advantage that black polyethylene-grown plants held in fruit ULR and led to a higher fruit RGR in hairy vetch during the later weeks of the season (Fig. 4). Therefore, higher total fruit production in the hairy vetch treatment resulted from relatively higher investment in

Fig. 3. Tomato cumulative fruit dry mass per plant. Regression equations are $Y = -207 + 33.0X - 0.0422X^2$ for plants grown with hairy vetch and $Y = -302 + 61.7X - 1.63X^2$ for plants grown with black polyethylene mulch based on model in Table 1 ($R^2 = 0.92$).

Fig. 4. Relative growth rate (RGR) of tomato vegetation (lines beginning at 6 weeks) and fruit (lines beginning at week 8) for plants grown with hairy vetch or black polyethylene mulch. Computations for both vegetation and fruit RGR were made per unit of vegetation mass.

leaf area and, ultimately, higher LAD. Longer LAD probably permits the production of sufficiently more photosynthate to compensate for lower photosynthate partitioning to fruit.

Explanations

Faster early growth of tomatoes in black polyethylene than hairy vetch has been attributed to faster warming of soil by black polyethylene (Teasdale and Abdul-Baki, 1995). Black polyethylene absorbs 96% of short-wave radiation while transmitting and reflecting very little (Ham et al., 1993). This absorbed radiation is conducted to the underlying soil and raises soil temperature. Teasdale and Abdul-Baki (1995) showed that soil temperatures were at optimum levels for tomato growth for more hours during the first 4 weeks of the season under black polyethylene than

under hairy vetch or bare soil. Exposure to warmer soils probably enhanced early tomato growth by enhancing root growth and nutrient uptake (Wien et al., 1993). Gent (1992) showed that nutritional deficiencies can develop in seedlings grown in cool soils.

Although black polyethylene can warm soils more rapidly to optimal levels early in the season, it can heat soils to harmful levels later in the season. Tindall et al. (1991) associated lower yields of tomatoes grown in black polyethylene than in straw mulch with excessive soil temperatures under black polyethylene during midsummer. Detailed measurements of soil temperatures across the bed profile by Teasdale and Abdul-Baki (1995), however, showed that soil temperatures at most sites within the bed did not exceed the optimum for tomato growth. Soil temperature only exceeded optimum at shallow depths on the shoulder of

Fig. 5. Unit leaf rate (ULR) of tomato vegetation (lines beginning at 6 weeks) and fruit (lines beginning at week 8) for plants grown with hairy vetch or black polyethylene mulch.

Fig. 6. Leaf area ratio (LAR) of tomato plants grown with hairy vetch or black polyethylene mulch.

the bed where the tomato canopy did not intercept radiation. Only a fraction of the total root length was found in these shallow, shoulder areas. Therefore, excessive soil temperature under black polyethylene during midsummer in our experiments can not explain better growth by hairy vetch than black polyethylene-mulched plants.

One defining difference between the mulch treatments in our experiments was N inputs. Although the black polyethylene plots received $56 \text{ kg} \cdot \text{ha}^{-1}$ more fertilizer N than the hairy vetch plots, hairy vetch residue had the potential of providing N at 167 and $197 \text{ kg} \cdot \text{ha}^{-1}$ in 1993 and 1994, respectively. All of this organic N probably would not be available for plant uptake, depending on mineralization rate and losses to leaching and denitrification. However, higher leaf N concentrations of tomatoes in the hairy vetch than those in the black polyethylene treatment (Abdul-Baki et al., 1996) suggests higher N availability with hairy vetch.

Many of the tomato responses to hairy vetch observed in this research, i.e., more biomass partitioning to foliage and leaf area as well as reduced early yield and increased late yield, also are attributes of tomatoes receiving high N. Hills et al. (1983) showed increased tomato vegetative than fruit growth at higher N. Wien and Minotti (1988) showed that high N stimulated a higher proportion of tomato vine growth relative to fruit yield and increased late yields. Delayed fruiting can not be explained by an adverse effect of high N on flowering or fruit set (Garrison et al., 1967), but Wien and Minotti (1988) suggested that enhanced foliage growth by high N may increase shading of fruit and result in delayed fruit ripening.

Tomato response to hairy vetch also may be attributed to factors other than N, as suggested by experiments defining the nitrogen requirements for tomatoes in these mulching systems (Abdul-Baki et al., 1997). For example, leaf N concentration of plants grown

with hairy vetch and no fertilizer N was higher than that of plants grown with black polyethylene and supplied with fertilizer N up to $392 \text{ kg} \cdot \text{ha}^{-1}$. Also, when supplied with optimum fertilizer N, yields of tomatoes grown with hairy vetch reached a plateau at higher levels than those grown with black polyethylene. The failure of N uptake and growth of tomatoes in black polyethylene mulch at high N levels to converge with those of tomatoes in hairy vetch suggest that hairy vetch enhances tomato growth by mechanisms other than supplementing N. Alternative mechanisms may include 1) improvement of soil physical properties by an organic mulch (Tindall et al., 1991), 2) reduction of foliar diseases that can interact with plant N status (Doss et al., 1975), or 3) a lower proportion of reflected far-red radiation that can influence the development of vegetative and reproductive growth in a manner similar to N (Decoteau et al., 1989).

Conclusions

This analysis demonstrated that tomatoes grown with a black polyethylene mulch were characterized by rapid early growth and partitioning to fruit resulting in higher early yield, whereas tomatoes grown with a hairy vetch mulch were characterized by increased partitioning to vegetation and leaf area resulting in higher total yield. Consequently, black polyethylene mulch is probably best adapted to areas of the country with a short growing season and premium prices for early-season tomatoes. In contrast, tomato production with a hairy vetch mulch will gain a yield advantage if the harvest season can be extended. This system would be adapted to areas with a long growing season and premium prices for late-season tomatoes.

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