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Greenhouse Microclimate for Tomatoes in the Southeast[1]

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Abstract. **Glasshouse microclimate during 3 growth periods in the Southern Piedmont region of the United States was characterized. An increase in density of tomato plants (*Lycopersicon esculentum* Mill.) by one-third, which doubled radiation interception, was suggested by early observations. Maintenance of clean glass surfaces was found to be particularly important during cloudy weather. There was no significant difference between mean air temperature and mean rooting media temperature in the raised beds used. CO_2 concentration was found to be low (240 ppm) when fans were not circulating outside air. CO_2 generators, installed to increase greenhouse CO_2 levels, were not effective possibly because control was inadequate. The use of CO_2 enrichment requires further study under Southeastern conditions. Relative humidity remained below the recommended 90% in the greenhouse except during cloudy-mild weather. Although inside relative humidity was generally less than outside relative humidity, values ranged from 90 to 100%.**

The demand for tomatoes is relatively uniform throughout the year. In the Southeastern United States, field tomato production is limited to a short period during the late spring and early summer and greenhouse-grown or imported tomatoes meet consumer demand during the remainder of the year. Although the greenhouse grower cannot match the cost of imported field-grown tomatoes, he can provide a fresher, higher quality fruit (13). Greenhouse tomato production has been successful in the North Central United States for many years (2). The industry in the Southeast is relatively new, but growing. The interest in the Southeast has been stimulated by agressive promotion of greenhouse manufacturers (13), need for alternative rural development enterprises, rising fuel costs and the appeal to part-time and retired workers.

An unpublished survey of R. Livingston (1972) by the Georgia Cooperative Extension Service in the mid 1960's showed that a high percentage of early growers in the Southeast failed in their greenhouse tomato production ventures. Failure was due to several reasons, including inadequate greenhouse microclimate control. There is little information on the microclimate in greenhouses in the Southeast in relation to recommended cultural practices including plant densities, temperature and CO_2 control, and sunlight utilization. The purpose of this research was to evaluate greenhouse microclimate under Southeastern growing conditions.

Materials and Methods

All observations were made in 1 of 2 glass greenhouses 9.4 × 15.25 m (30 × 50 ft) with a volume of 638 m^3. Both were oriented in north-south (long axis) direction at the Southern Piedmont Conservation Research Center, Watkinsville, Georgia (83° 35' W, 33° 52' N). The greenhouses were planted to tomato in a fall-spring sequence in a pine-bark, vermiculite mixture contained in long, narrow raised beds, described by Pallas et al. (16) and Bruce et al., (3). The plants were pruned to a single stem (Fig. 1) entwined up a rope suspended from the roof. Thermostatically controlled hot-water radiators along the walls provided heat, and thermostatically controlled fans (delivering about 340 m^3/min of air) pulled air through north

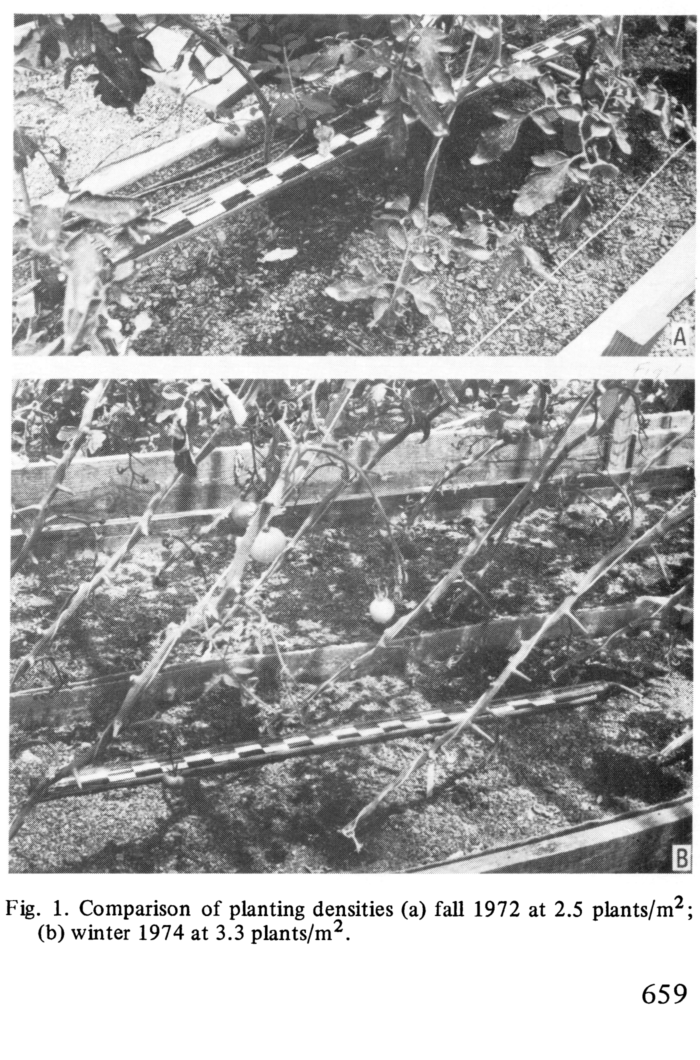

Fig. 1. Comparison of planting densities (a) fall 1972 at 2.5 plants/m^2; (b) winter 1974 at 3.3 plants/m^2.

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[5]Trade names are included for the benefit of the reader and do not imply preferential endorsement of any product by the authors or the U.S. Department of Agriculture.

wall vents and out south wall vents to cool the greenhouse. With the fans operating, the residence time of air in the greenhouse was approximately 2 min. Minimum air temperature in the greenhouse was set for 18°C at night and 22°C during the day for sunny weather. For cloudy weather, temperatures were maintained above 16°C and 20°C, respectively.

Microclimate data were taken during 3 cropping periods: fall, 1972; winter, 1973; and winter, 1974. The first tomato crop (fall, 1972) was planted at a recommended density (2) of 2.5 plants/m^2 (24,646 plants/ha), using a planting configuration of 45- × 45-cm plant spacing, with 2 rows between walkways (Fig. 1A). Removal of 1 of the walkways enabled planting the next 2 crops at a density of 3.3 plants/m^2 (32,862 plants/ha) (Fig. 1B).

Measured microclimatic variables included solar radiation, ambient air temperature, humidity, and CO_2 both inside and outside the greenhouses. Solar radiation was measured with Eppley[4] pyranometers above and within the 2 greenhouses. Radiation at the plant bed surface was measured with spatially-integrating pyranometers constructed for measurement of radiation within plant canopies (7). Measurements were made to determine solar irradiance through only the plants and through both the plants and access walkways combined. Aspirated wet-dry bulb psychrometers were used for temperature and humidity measurements within the greenhouses at 2/3 plant height and outside the houses at 1-m height. Average leaf temperature was measured by placing small thermocouples (0.13 mm diameter) against the leaf surfaces. Locations on the plants and sites in the greenhouses were randomly selected. CO_2 was spatially sampled in the greenhouse by pulling air with individual metal bellows pumps from perforated tubes (with progressively larger holes extending from the greenhouse center to the sides). Air was then transmitted to a research trailer nearby via heated nylon tubes into sample bags constructed of a polyethylene-aluminum-mylar material for temporary storage. The air was subsequently measured for CO_2 content with an infrared analyzer. CO_2 enrichment in the greenhouse was accomplished with a natural gas, CO_2 generator. (No. 1332 CO_2 Generator, Johnson Gas Appliance Co., Cedar Rapids, Iowa; the natural gas generator delivers 17,600 W heat and 108 g CO_2/min when operated at a design gas pressure of 10.2 g/cm^2.) The generator was used as an additional heat source and on-off regulation was in response to temperature.

Rooting media temperature was measured at three vertical depths – at the media surface (1 cm below); at the watertable surface (18 cm); and half-way between – with thermopiles of copper-constantan wire embedded in copper rods.

Five tomato cultivars, 'Floradel', 'Tuckcross 520', 'Tuckcross 533', 'Tropic', and 'Super M.' were grown in the 3 seasons of greenhouse studies reported here. Sixty-four days of observation were made during the 3 cropping periods and 3 general weather types were selected for discussion: cold-sunny, cloudy, and mild-sunny.

Harvested fruit were weighed and classified into marketable and nonmarketable fruit. Nonmarketable fruit had defects and disorders described by Brooks (2). Most of the nonmarketable fruit resulted from fruit cracking so 2 classifications were established, nonmarketable cracked and nonmarketable "other". Nonmarketable "other" classification included blossom-end rot, blochy ripening, anther scars, green shoulder, misshapened fruit, and catface scars.

Results and Discussion

Solar radiation. Table 1 compares solar radiation reduction through clean, dirty, and fogged (moisture condensation on the inner glass surface) glass under various weather conditions. Since light saturation of greenhouse tomatoes is not likely (considering the entire canopy) any decrease in light flux density can reduce total photosynthesis. Under very low light

Table 1. Solar radiation reduction in glasshouses at Watkinsville, Georgia, during winter.

Weather type	Glass condition	Outside radiation (solar noon)	Glasshouse % radiation reduction
Clear sky	clean	558-698 W/m^2	10-15%
Cloudy sky	clean	70-140	50-60%
Clear sky	dirty	488-698	25-35%
Cloudy sky	dirty	70-209	55-65%
Clear sky	fogged	558-698	65-80%

conditions (as are commonly experienced for extended periods during our rainy winters), a loss of 50% of available sunlight might be sufficient to cause floral abscision due to low photosynthesis. Fogged glass decreases total solar radiation by a large percentage (Table 1). This may not be a serious problem, however, since the photosynthetically active region of the solar spectrum is not as efficiently absorbed by water (moisture condensation) as is the near infrared region. The energy content in both spectral regions was not evaluated inside the greenhouse.

In the first fall crop when the plants were about 2 m tall, 15 to 25% of available solar radiation within the leaf canopy was transmitted to the bed surface during a 1-hr period at solar noon. About 30 to 70% of the total available solar irradiance was transmitted to the greenhouse floor through the combined leaf canopy and walkway areas. Thus, only 30 to 40% of available solar flux density was intercepted by the plants.

Because of the apparent high loss of solar radiation to the floor and beds, the planting density was increased to 3.3 plants/m^2 for the following 2 crops. At this higher density, 60 to 70% of the available solar flux was intercepted by the plants.

Air and plant-media temperature. The hot-water radiator heating system maintained excellent temperature control within the greenhouse when the outside temperature was less than 15-18°C. When the temperature increased above the set temperature, fans pulled in outside ambient air for cooling. Under high solar flux density (>550 W/m^2), inside air temperature ranged as high as 10°C above outside air temperature. Leaf temperature was about the same as greenhouse air temperature (± 3°), regardless of radiation conditions.

Growing media surface temperature closely followed the greenhouse air temperature rather than the watertable temperature and was strongly influenced by solar radiation around solar noon. At the water surface, media temperature was quite constant, since it was influenced by the incoming water temperature. The mean root zone temperature (halfway between the water and media surface) did not differ significantly (5% level) from the greenhouse mean air temperature, although the variation in air temperature was much greater, as might be expected (Table 2). Minimum rooting-media temperature did not differ significantly (5% level) from minimum greenhouse air temperature; however, maximum rooting media temperature was significantly (5% level) lower than maximum air temperature. Mean root zone temperature (Table 2) was lower than the optimum recommended (18) root-zone temperature of 25°C, but it was substantially above the lower limit of 14° reported by Martin (12). Others (1, 2) recommend maintaining root temperature around 20° to avoid excessively vigorous growth, which can reduce fruit set or slow fruit growth. Soil-warming experiments in corollary studies (9) did not increase early yields, as had been reported by others (17, 18), nor were total yields fruit size, or flower formation increased.

Carbon dioxide concentration and enrichment. In greenhouse production, CO_2 enrichment can produce spectacular yield increases, (5, 19, 20, 21). Wittwer and Robb (21) and

Table 2. Comparison of rooting media temperature with ambient outside and greenhouse temperature between February 5 – April 11, 1974.

Temperature	Temperature (^oC) Air[z] outisde	Air[y] inside	Rooting[x] media
Minimum	4.3 ± 3.2[w]	16.0 ± 2.3	17.3 ± .4
Maximum	19.1 ± 3.4	23.5 ± 1.3	19.7 ± .6
Mean	11.4 ± 2.4	20.4 ± 1.7	18.9 ± .9

[z]Measured 1 m above a closely cut grass surface.

[y]At 2/3 canopy height in middle of greenhouse.

[x]Root zone measurement at 9 cm below soil surface (half of distance between the surface and watertable).

[w]Small sample distribution test (t) at 5% level.

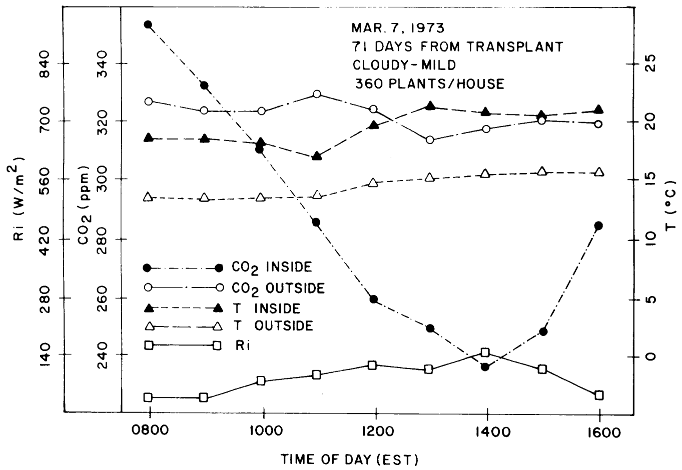

Fig. 3. Glasshouse microclimate under cloudy-mild climatic conditions.

Morgan (15) indicated CO_2 enrichment during early growth gives plants the potential of developing flowers earlier and thus producing mature fruits earlier. Madsen (11), however, did not conclude that CO_2 addition would be beneficial for young tomato plants. He reasoned that since growth rate decreases with plant maturity, the increased early growth rate might hasten senescence of the first leaves. Wittwer and Honma (20), however, reported that growth rates can be increased by 50 percent and early flowering accelerated by 7 to 10 days. Beneficial effects of CO_2 enrichment during early growth reportedly extended into the fruiting period, increasing top and root growth, flower formation, and gave more rapid recovery after transplanting. Total yield increases of 14 to 30% have been reported with CO_2 enrichment (2, 4), along with early crop increases of 90%. Even though the benefits of CO_2 enrichment would appear obvious, greenhouse CO_2 enrichment is not a recommended practice in the Southeast because no practical method has been developed for controlling CO_2 in the normally relatively mild and changeable Southeastern (winter) weather, where ventilation for cooling during high solar radiation periods may be required (8).

Fig. 2. shows the relationship between solar radiation intensity (Ri) and inside and outside CO_2 concentration and air temperature (T) for a cold-sunny day. Inside air temperature remained relatively constant, with a slight increase after solar noon (about 1230 hr EST), while the outside air temperature decreased slightly due to a passing cold front. Outside, there was evidently little photosynthesis and ambient CO_2 decreased only slightly at 1 m above a grass surface. By 0800 hr EST, photosynthesis in the glasshouse was sufficient to decrease the

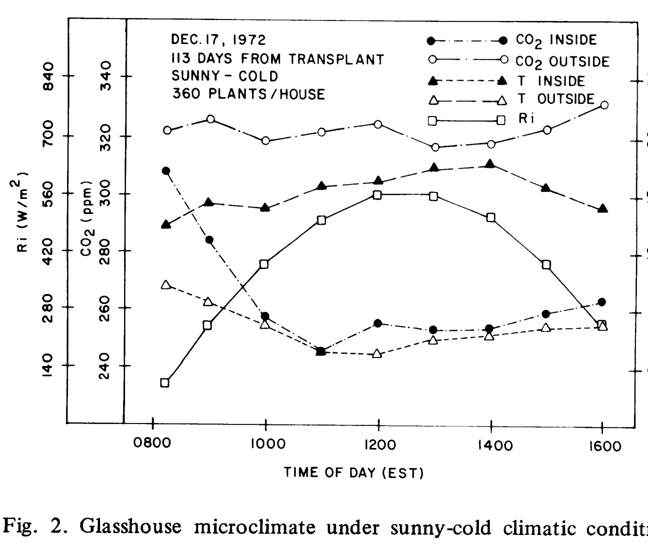

Fig. 2. Glasshouse microclimate under sunny-cold climatic conditions.

inside CO_2 concentration below the outside ambient concentration. That is, by the time the sunlight had reached less than 25% of its maximum daily value, photosynthesis and leakage had decreased the nighttime CO_2 concentration to near that of the outside ambient concentration (24-hr data acquisition indicated that nighttime CO_2 levels typically increased to 600 ppm due to plant respiration and soil organic matter decomposition). Photosynthesis decreased the inside CO_2 to 245 ppm (by volume) at 1100 hr EST, at which time the CO_2 use and replenishment by air leakage stabilized. Others (14) have reported even lower glasshouse CO_2 concentrations (170-180 ppm). Plastic greenhouses are generally more airtight than glasshouses, thus inside CO_2 concentration in them could possibly be reduced even more. Benefits of CO_2 enrichment for greenhouses in the Southeast appear possible, and seemingly, photosynthesis could be increased considerably.

Extended periods of cloudy-mild weather in the Southeast during late winter are more amenable to CO_2 enrichment. Fig. 3 is an example of glasshouse microclimate during a prolonged cloudy period in late winter. Solar radiation (Ri) remained very low all day, with little change in outside temperature and CO_2 concentration. However, some photosynthesis was indicated by the decrease in CO_2 level inside the greenhouse. Again, like in Fig. 2, the CO_2 concentration was depleted to about 240 ppm during the period of highest solar radiation (about 1400 hr EST). Shortly afterwards, solar radiation and photosynthesis decreased due to decreased radiation and the CO_2 level increased from CO_2 diffusion into the greenhouse. We experienced several successive days of this type weather and we suspected that these extended periods of low photosynthate production caused our observed floral abscission. This problem might have been lesseded if high CO_2 levels had been maintained artificially to increase photosynthesis since there is no evidence that light, even in very cloudy weather, is so limiting that plants cannot use extra CO_2 (20).

A glasshouse microclimate for a typical fall or late winter cool night and early morning with warm days is depicted in Fig. 4. Ambient CO_2 concentration decreased from a nighttime high to a daytime minimum of about 305 ppm. Plants in the greenhouse depleted the nighttime CO_2 levels to well below ambient concentrations by 0800 hr EST. At 0815 hr EST the greenhouse ventilation fans came on intermittently and maintained an average CO_2 of 320 ppm. After 0915 hr EST the fans remained on and greenhouse CO_2 levels were maintained slightly below ambient concentration. Cool nights and early mornings followed by warm days is not a situation suitable for greenhouse CO_2 enrichment except during the early morning hours.

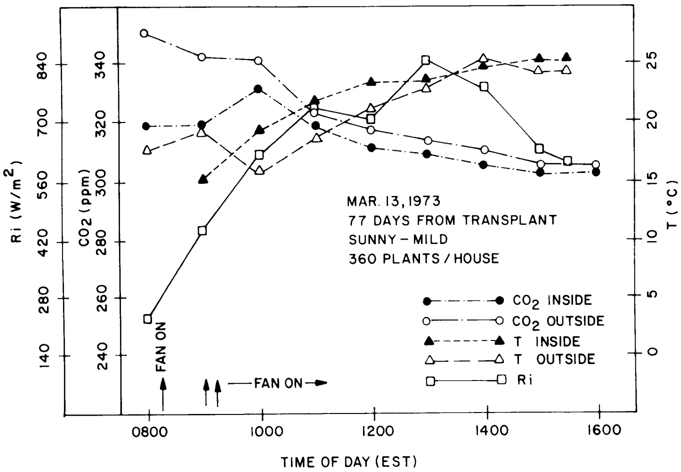

Fig. 4. Glasshouse microclimate under sunny-mild climatic conditions.

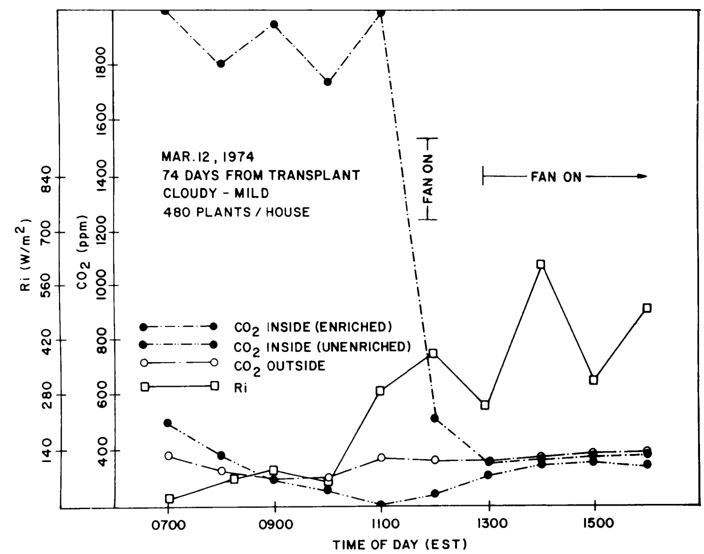

Fig. 5. Comparison of CO_2 enriched and unenriched glasshouse microclimate.

Fig. 5 shows a comparison of CO_2 levels of 2 greenhouses, side by side, with identical treatments, except one had artificial CO_2 enrichment. The morning was completely overcast with intermittent rains and low solar radiation intensity (Ri). CO_2 concentration in the unenriched house decreased from the nighttime high of about 500 ppm to about 200 ppm by 1100 hr EST. During this same period the CO_2 generator in the enriched house fluctuated on and off but maintained a morning concentration above 1700 ppm. After a heavy rain at 1045 hr EST, solar radiation through the intermittent clouds increased air temperature in the glasshouse until the fans came on. The enriched CO_2 was quickly exhausted from the glasshouse (Fig. 5), indicating the need for some means of CO_2 generator control.

Humidity. High relative humidity should be avoided in greenhouses, since a high humidity favors development of certain plant diseases (2, 10). Relative humidity under sunny-cold days ranged from 43 to 74% with a days's mean of 62% (Fig. 2) which is well below the recommended maximum relative humidity of 90% (2). However, the Southeast winter has long periods of cloudy-mild weather. During these periods, the fans were not actuated and relative humidity in the greenhouse approached 100%, causing condensation on the inner glass surfaces. Fig. 5 shows an example of cloudy-mild weather conditions where the ventilation fans were not actuated. Under these conditions, greenhouse relative humidity ranged from 90 to 100% with a day's mean of 96%. However, inside relative humidity was slightly below that outside (99 to 100%) because of heating the inside air. During days of mild weather (Fig. 4), air exchange fans were actuated, and the greenhouse relative humidity followed closely the outside relative humidity.

Greenhouse air exchange. How much air is lost to the outside depends on the temperature gradient between inside and outside. An attempt was made to measure CO_2 leakage from the greenhouse on a completely overcast day (selected to minimize temperature fluctuations) between growing seasons. CO_2 was released into the glasshouses to a concentration of 1000 ppm and then the concentration decrease with time was measured. For the existing weather conditions, the air exchange rate was calculated from the depletion rate to be about 10 m^3 air/min or about 3% of the ventilation-forced air exchange rate. The windspeed and temperature differential between inside and outside during the measurement period were typical of wintertime growing conditions.

CO_2 loss and gain was calculated using the observed mass flow air loss. With a CO_2 enrichment concentration of 1000 ppm, CO_2 loss was calculated to be 112 cm^3 CO_2/sec. Our generator produced 463 cm^3/sec CO_2; thus, about 25% of the enrichment gas was required to maintain the 1000-ppm level due to mass flow air leakage alone. Likewise, assuming this same air-loss rate for an unenriched glasshouse during sunny-cold days (Fig. 2), at an inside CO_2 concentration of 250 ppm, the CO_2 gain by mass flow would amount to 13 cm^3/sec or an equivalent photosynthetic rate of 8.7 mg CO_2/min/plant in the glasshouse.

Heat loss due to mass flow by leakage amounted to 2.135 kw for the existing weather conditions. Heat loss from glasshouses appears to be quite high (due to mass flow leakage) when compared to that from plastic greenhouses. However, the energy loss in plastic greenhouses due to outward transmittance of longwave radiation is much larger than that in glass greenhouses. Thermal transmittance of glass is 4.4% compared to 12, 16, and 71% of polyvinyl, mylar (polyester), and polyethylene, respectively (6).

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Breeding Strawberries for Fruit Firmness[1]

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Abstract. **Heritability estimates for fruit firmness of strawberry (*Fragaria* X *ananassa* Duch.) based on the regression of mean offspring performance on average parent performance varied from 0.49 to 0.67 over a 4 year period. Analysis of variance of progeny data showed that general combining ability variance (additive) was much greater than specific combining ability variance. Of 29 parent clones studied 'Holiday', 'Linn', 'WSU 1522' and 'MD-US 3184' had the firmest fruit and on the basis of progeny analysis had the highest general combining ability parental values. Low parental values were obtained for 'Tamella', 'Benton', 'Puget Beauty', 'WSU 1019', 'OR-US 3291' and 'OR-US 3522'.**

Improvement in fruit firmness is a major objective of many strawberry breeding programs. Firm fruited cultivars are more suited to fresh market shipping, show less damage in mechanical harvesting and when processed retain their texture better than cultivars with soft fruit.

Objective evaluations of fruit firmness are routinely used by breeders and are relatively simple (3, 4, 7, 8, 9, 11). However recommended breeding strategies and suggested methods for selecting parents and superior progenies have varied. Hansche et al. (7) obtained moderately high heritability estimates for fruit firmness and suggested that selection based on parental phenotype would result in significant and predictable gains among offspring. On the other hand Spangelo et al. (12) obtained low estimates of heritability and significant nonadditive variance and suggested that progeny testing should be used to determine the superior families from which subsequent selection could be made. This study was undertaken to clarify the nature of inheritance of fruit firmness in strawberry by estimating heritability over a 4-year period and determining the importance of general (additive) and specific combining abilities.

Materials and Methods

Fruit firmness was measured as puncture force, the force (g) recorded on a Chatillon push-pull gauge (Model 516-500) necessary for a 5 mm diameter flat rod to penetrate into a ripe fruit. Each year puncture force determinations were based on an evaluation of three fruits at each of four harvest dates. Phenotypic assessment of 12 cultivars and 13 advanced selections (all subsequently referred to as clones) was made over a 4-year period. Puncture force determinations were also made on the fruit of more than 2,400 seedlings from 119 progenies involving 29 parent clones. In each year 21 seedlings from each progeny were planted in three blocks of seven seedlings each. Each seedling plot consisted of a matted row 1 m in length. Within each block two plots of each parent clone were planted. Due to plant death and sterility not every seedling could be evaluated.

In each of 4 years heritability estimates (h^2) were determined from the linear regression of mean offspring performance on average performance of their parents (5). Progeny puncture force evaluations were analyzed each year by a procedure suggested by Gilbert (6) for data from many crosses not made in a systematic manner. The procedure estimates general combining ability (GCA) and specific combining ability (SCA) variances and determines their significance. The procedure also determines GCA parental values as a guide in breeding.

Results

Phenotypic assessment of puncture force for parent clones showed large differences between clones with 'Holiday', 'Linn', 'WSU 1522', and 'MD-US 3184' having very high values (Table 1). The clones with the softest fruit were 'Olympus', 'Rainier', 'Puget Beauty', 'WSU 1019' and three OR-US selections '3291', '3522' and '3551'.

Large differences were observed between parent clones in GCA parental values. High parental values were found for 'Holiday', 'Linn', 'MD-US 3184' and 'WSU 1522' while low values were obtained for 'Tamella', 'Benton', 'Puget Beauty', 'WSU 1019', 'OR-US 3291' and 'OR-US 3522' (Table 1). Over the 4-year period GCA parental values and phenotypic assessments of puncture force were correlated ($r = 0.75$, $n = 43$).

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