Spatial and Temporal Distribution of Ripe Muskmelon Fruit

Yael Edan

Department of Industrial Engineering and Management, Ben-Gurion University of the Negev, POB 653, Beer Sheva 84105, Israel

James E. Simon

Horticulture Department, Purdue University, West Lafayette, IN 47907-1165

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Abstract. The spatial distribution patterns of five melon cultivars (*Cucumis melo* L. var. *reticulatus*) were evaluated by measuring XY coordinates of ripe fruit locations in the field. Fruit ripeness distribution over time was also evaluated for three cultivars by measuring the number of ripe fruit, fruit mass, and location over time. Spatial distribution curves for distances between fruit clusters and individual fruit from cluster centroids varied between clusters and were derived for each cultivar from the best fit curves based on chi-square analysis from the two-dimensional spatial fruit distribution. These equations can be used for predicting actual fruit locations in the field. Ripeness distribution patterns indicated that, while the exact duration of the effective harvesting period is cultivar-dependent, the ripeness trend for each of the cultivars was similar. Spatial distribution patterns vary among melon cultivars and must be recognized in the design of automated harvesting systems.

A mechanized system for melon harvesting would reduce tedious labor and peak labor requirements. While a single destructive harvest of melons would be highly desirable from an engineering standpoint, the lack of commercially marketable muskmelon cultivars that ripen uniformly and over a short interval have precluded this as a viable economic option (Harriot et al., 1970). A possible solution for mechanical harvest could be a robotic system that selectively harvests ripe fruit. Such a prototype system has been developed (Edan et al., 1994). The performance of a robot acting in an agricultural environment is highly dependent on the spatial geometry of the crop, fruit distribution (Edan and Miles, 1993), and cultural practices. Cultural practices, such as plant density, rate of nitrogen fertilization, training of the vines, and the application of ethephon on melons, each can influence the percentage of fruits that ripen over a concentrated interval. However, no practice was sufficient to economically justify a single destructive harvest (Harriot et al., 1970; O'Brien and Harriott, 1975; O'Brien and Lingle, 1966; O'Brien and Zahara, 1971).

To our knowledge, little descriptive information on muskmelon fruit growth and development is available. McGlasson and Pratt (1963) showed that the growth of the individual muskmelon fruit resembles a sigmoid curve, as found with other cucurbits. Influence of irrigation and nitrogen fertilization on yield, quality, and muskmelon size has been described by Flocker et al. (1965). As muskmelon within-row plant spacing increased from 25 to 100 cm, yield (kg) per plant, number of fruits per plant, fruit mass, and soluble solids concentration increased linearly, whereas number of culls and marketable fruits per hectare decreased linearly (Bhella, 1984). Lazin and Simonds (1981) found that increasing the distance between plants increased the number of fruits per plant and mean fruit mass, but decreased the total number and mass of muskmelons in a given area. Holliday (1960) explained the relationship between plant population and crop yield as a parabolic curve.

None of these earlier studies on melon crop growth examined the two-dimensional spatial distribution of the fruit's physical location in the field, and only a few examined the ripening patterns of cultivars over time (McCollum et al., 1987; McGlasson and Pratt, 1963). An earlier preliminary study suggested that the planting pattern of melon may alter the actual fruit location, but had little effect on the actual spatial distribution of fruit (Edan and Miles, 1993). The speed of a robotic system depends on the spacing between the immature fruits and the ripe fruits. The knowledge of the temporal distribution of the fruit is also essential for developing a continuous harvesting system (Edan and Miles, 1993). The objective of our study was to examine and analyze the spatial and temporal distribution of muskmelon fruit in a typical field cropping system. Specifically, two-dimensional fruit locations

and the ripening of fruit during the season were analyzed for five muskmelon cultivars.

Materials and Methods

Fruit distribution patterns were initially investigated for the cultivar Superstar in 1989. Physical location of the fruit from 'Superstar' were collected by measuring XY coordinates of 859 melons in 29 rows at the Southwest Purdue Agricultural Center, 7 km north of Vincennes, Ind. 'Superstar' melons were transplanted into rows spaced 3.6 m apart with plants 0.9 m apart within the rows. The plants were fertilized, irrigated, trained, and field-grown as recommended by Purdue Univ. (Latin et al., 1989). Training consisted of once manually placing the growing vines on the black plastic along the row. Trickle irrigation lines placed beneath black plastic mulch provided water as needed. Nitrogen was added as a broadcast and plowdown application with actual N at 101 kg·ha⁻¹.

The exact coordinates of each individual fruit were measured. Spatial distribution is defined as the physical coordinates of fruit location in the field. The spatial distribution of the fruit in the field from all 29 rows was statistically analyzed using the International Mathematical and Statistical Library (IMSL, 1988). The average distance between adjacent fruit along the row (X) and the average distance between fruit across the row (Y) was calculated. As the number of fruit and their distribution depends on plant spacing and cultural practices, in addition to the specific cultivar, the average distance of fruit along the row, average distance between plants along the row, the number of fruit clustered by each plant center, and the average distance of the fruit from the plant center in the X and Y directions were also analyzed. Clusters of melons, defined here as the grouping of 1–5 fruit, were derived using statistical cluster analysis (Walpole and Myers, 1985).

The distance between fruit clusters was determined by a hierarchical cluster analysis using Ward's method (Andersberg, 1973). The distance criteria for the cluster analysis was computed as the Euclidean distance along the row (X direction), since this fits the growing pattern of the melons planted in equal distances along the X axis. Clusters were generated such that the increase in the within-cluster sums of squares were minimized (Andersberg, 1973). Distances were computed by the distance between centroids (defined as the average X and Y distances between the fruit belonging to the same cluster). Thus, the minimum increase in the error sum of squares is proportional to the squared Euclidean distance between the centroids of the merged clusters. The use of cluster analysis appears appropriate, as melon fruit develop in groups. Distribution curves were fitted to the histograms of clusters, and the chi-square test was used to test the goodness of fit (Walpole and Myers, 1985).

This study was repeated at the same location (Vincennes, Ind.) in Summer 1991, and expanded to include the following cultivars:

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'Makdimon' (214 fruit in three rows), 'Mission' (250 fruit in three rows), and 'Starship' (209 fruit in two rows), in addition to 'Superstar' (182 fruit in three rows). These cultivars were added to determine whether spatial distribution patterns of fruit vary among melon cultivars, and included two Midwestern or eastern melons ('Superstar' and 'Starship'), one western shipper ('Mission'), and a green-fleshed melon ('Makdimon'). Production was as described in 1989, but in 1991, plant spacing simulated commercial recommendations with rows 2 m apart and plants 1.2 m apart within the rows.

In late Fall 1990, data from 218 melons in three rows were also obtained for 'Galia' (a green-fleshed melon) grown in a commercial field in the southern Jordan Valley, Israel, to provide an additional cultivar grown under very different environmental conditions. Rows were 1.2 m apart with plants 0.3 m apart within the rows.

The maturity date for all fruit over the 1991 season was measured in Vincennes, Ind., for the following cultivars: 'Superstar', 'Mission', and 'Starship'. Harvest data on mass and number of ripe and marketable fruits were collected at 2- to 3-d intervals to characterize the ripeness distribution over time. X and Y coordinates of ripe fruit were also measured.

Results and Discussion

Spatial distribution of 'Superstar' fruit, 1989. In a representational two-dimensional plot of the XY spatial distribution of all melon fruit in six randomly selected adjacent rows, the average distance between adjacent fruit along a row (X axis) was 34 ± 10 cm (Fig. 1). The average Y distance between adjacent fruit within a row was 23.6 ± 14.2 cm. The distribution curve illustrating the average within-row distance to the nearest fruit (Fig. 2a) shows that 22% of the fruit are ≤ 20 cm apart and that 37% of the fruit are from 21–40 cm apart, with $\approx 75\%$ of all fruit located within 60 cm. These findings have an effect on the design of the robotic harvester, since a minimum number of harvesting arms would be required for optimum efficiency, as most of the fruit are concentrated along the center of the row (Edan, 1990).

Spatial distribution of fruit clusters was similar to that of individual fruit. The distribution curve of the distances between fruit clusters (Fig. 2b) and the distances of the individual fruit from the cluster centroid (Fig. 3) were derived by testing the goodness of fit of gamma, logarithm, and exponential distribution curves following cluster analysis. The chi-square values for each curve, as derived from the statistical analysis, indicate the best fit curve being the gamma curve, as it has the lowest chi-square value (Table 1). The parameters for the gamma distribution curve are shown in Table 2.

Fruit clusters were close together, with more than 37% of the fruit clusters within 20 cm of each other, and with fewer than 36% of fruit clusters being 60 cm or more apart (Fig. 2b). Fruit within a cluster were close to the

Fig. 1. Spatial distribution of 'Superstar' muskmelon fruit, in six adjacent rows, Vincennes, Ind., 1989. Individual fruit shown as '[]'.

Fig. 2. Distribution curve of (a) within-row distance to nearest 'Superstar' muskmelon fruit; (b) within-row distance between muskmelon clusters, Vincennes, Ind., 1989.

cluster centroid. Thirty-five percent of the fruit were within 20 cm from the cluster centroid and fewer than 33% of the fruit clusters were ≥ 60 cm apart from the cluster centroid in the X direction (Fig. 3). From the cluster centroid in the Y direction, 52% of the fruit clusters were within 20 cm, and $< 8\%$ were ≥ 60 cm apart (Fig. 3).

Preliminary field studies on changing the spatial planting pattern of 'Superstar' while maintaining an equal plant density (Edan and Miles, 1993) supported the concept that fruit distribution patterns correspond to the gamma distribution curve. This finding suggests that, unless plant-to-plant competition occurs, alterations in the planting pattern will not affect the overall distribution pattern, although the actual fruit location may be altered by planting pattern.

Comparison of fruit distribution among muskmelon cultivars. The maximum distance between fruit clusters among cultivars was 63 cm for 'Superstar', and the minimum was 35 cm for 'Mission' (Table 3). The maximum distance between fruit between rows was 24.4 cm for 'Galia'; the minimum, 5.6 cm, was for 'Superstar'. The maximum average distance between adjacent fruit was 20 cm for 'Superstar' and the minimum was $\approx 52\%$ less for 'Mission' and 'Galia'.

Fruit ripeness over time. Wide variation in the accumulated number of fruit (Fig. 4) and fruit mass (Fig. 5), as a function of harvest date, existed for the cultivars Mission, Starship, and Superstar.

Maximum fruit count and mass were achieved 77 d after initial sowing in the greenhouse or 57 d after transplanting for 'Superstar' and 'Starship', and 59 d after transplanting for 'Mission' (Fig. 5). By this date, a total of 39%, 27%, and 28% of the fruit were ripe for 'Superstar', 'Starship', and 'Mission', respectively.

Summary and Conclusions

The spatial fruit distribution of five muskmelon cultivars was evaluated by measuring XY coordinates of fruit locations in the field. Ripeness distribution was evaluated for three cultivars by measuring the accumulated number of ripe fruit, fruit weight, and location over time.

The two-dimensional spatial fruit distribution was mathematically derived and can be used for predicting actual locations of fruits in the field. The distribution curves selected for each parameter were the best fit curves based on chi-square analysis. Distribution parameters (distance between consecutive fruit, distance between plants, and distances of fruit from the plant cluster centroid) are cultivar-dependent and have been derived for each cultivar.

Despite the variation in accumulated fruit count and fruit weight by the cultivars, these results do show that there is an optimum harvest window after which the efficiency of collection would be reduced due to few newly maturing fruit. While the absolute number of ripe fruit harvested each day would presum-

Fig. 3. Distribution curve of the within row (X) and between row (Y) distances from 'Superstar' muskmelon cluster centroid, Vincennes, Ind., 1989.

Table 1. Chi-square fit of distribution curves of melon locations.

Distribution	Exponential	Gamma	Logarithm
X distance between clusters	433377	0.510813	9.00486
X from cluster centroid	360323	0.316817	8.53319
Y from cluster centroid	820797	0.10644	7.37293

Table 2. Gamma distribution parameters for melon locations.

Distribution	α^2	β
X distance between clusters	13.9856	0.981409
X from cluster centroid	14.4108	0.981409
Y from cluster centroid	24.9867	1.0053

² α , β are parameters of the Gamma distribution (Walpole and Myers, 1985).

Table 3. Average distances for selected spatial characteristics of fruit location among melon cultivars.

Cultivar	Distance (cm) ^a		
	A1	A2	A3
Mission	13.1	6.1	35
Makdimon	19.4	5.9	56
Superstar	18.2	5.6	63
Galia	13.4	24.4	39
Starship	20	5	47

^aA1 = Between fruit within the row (X); A2 = between fruit across the row (Y); A3 = between cluster centers.

ably be affected by seasonal and cultural influences, we did not quantify this impact. Rather, we can suggest that an understanding of the harvest window is important in predicting the number and intervals between selective harvests.

'Mission', the only western shipping melon used in this study, had the smallest distance between fruit clusters. 'Superstar' represented the opposite extreme. As the performance of a robotic melon harvester increases as the distance between fruit clusters increases (Edan and Miles, 1993), our data show that 'Superstar' would be the preferred cultivar and that cultivar selection markedly influences the efficiency of robotic harvesting of muskmelons.

Ripeness distribution patterns indicated that the majority of fruit are collected within the

first 15 d of harvest. While the exact duration of the effective harvesting period is cultivar-dependent, the ripeness trend for each cultivar is similar. The time period of greatest increase in accumulated ripe fruit would be the most efficient for mechanical harvesting. Based on the rapid rate of fruit ripening within the first 10 d of harvest for each cultivar, selective harvesting would need to occur at no more than 2-d intervals. This conclusion suggests that more planting dates would extend the efficient utilization of a mechanized selective harvesting system.

The fruit distribution patterns of muskmelons could be used in the design of the travel path, the vision-processing algorithms for detecting the location of melons, and the sensor algorithms for detecting ripe fruit in robotic

Fig. 4. Average cumulative count of ripe fruit in six randomly selected rows for 'Mission', 'Starship', and 'Superstar' muskmelons, Vincennes, Ind., 1991.

Fig. 5. Average cumulative mass of ripe fruit in six randomly selected rows for 'Mission', 'Starship', and 'Superstar', Vincennes, Ind., 1991.

harvesting. Spatial fruit distribution patterns vary among melon cultivars and, therefore, must be considered in the design of all mechanized systems, such as those envisioned for directed sprayers for insects, diseases, fertilizers, and weed control, in addition to automated harvesting systems.

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