Changes in Chlorophyll Fluorescence of Apple Fruit during Maturation, Ripening, and Senescence

Jun Song¹, Weimin Deng², and Randolph M. Beaudry³

Department of Horticulture, Michigan State University, East Lansing, MI 48824

Paul R. Armstrong⁴

Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK 74078-0497

Additional index words. *Malus ×domestica*, maturity, firmness, quantum yield, variable fluorescence, controlled atmosphere, sorting

Abstract. Trends in chlorophyll fluorescence for ‘Starking Delicious’, ‘Golden Delicious’ and ‘Law Rome’ apple (*Malus ×domestica* Borkh.) fruit were examined during the harvest season, during refrigerated-air (RA) storage at 0 °C, following RA and controlled-atmosphere (CA) storage, and during a poststorage holding period at 22 °C. Fluorescence parameters of minimal fluorescence (Fo), maximal fluorescence (Fm), and quantum yield [(Fm-Fo)/Fm, otherwise denoted as Fv/Fm] were measured. During ‘Starking Delicious’ fruit maturation and ripening, Fv/Fm declined with time, with the rate of decline increasing after the ethylene climacteric. During RA storage, all fluorescence parameters remained constant for approximately 2 weeks, then steadily declined with time for ‘Starking Delicious’ fruit. Superficial scald was detected after Fv/Fm had declined from an initial value of 0.78 to ≈0.7. Fv/Fm was consistently higher for CA-stored fruits than for RA-stored fruits. We were able to segregate combined populations of “high-quality” (CA) and “low-quality” (RA) ‘Law Rome’ fruit with 75% accuracy using a threshold Fv/Fm value of 0.685, with only 5% RA-stored fruit incorrectly identified as being of high quality. During a poststorage holding period, Fo, Fm, and Fv/Fm correlated well with firmness for ‘Starking Delicious’, but not for ‘Golden Delicious’ fruit, which were already soft. Fo and Fm were linearly correlated with hue angle for ‘Golden Delicious’ fruit, decreasing as yellowness increased. The accuracy, speed of assessment, and light-based nature of fluorescence suggests that it may have some practical use as a criterion to assist in sorting apple or other chlorophyll-containing fruit or vegetables on commercial packing lines.

The high level of competition in domestic and international markets for stored apple fruit requires high-quality, packed fruit. Segregating high- and low-quality fruit is an important component of quality control of the final packout. While packinghouses are able to segregate individual fruit by color and size, they are unable to sort each fruit by condition (e.g., flesh firmness, sugar content, ratio of sugars to titratable acidity and aroma) and ability to retain these quality attributes.

Much of the research on apple fruit quality has focused on firmness measurement as a means of assessing textural attributes such as

crispness and juiciness (Lovelidge et al., 1987). Firmness is considered to be the most important overall quality attribute of apple fruit selected by consumers (Dull and Hulme, 1971). Firmness is typically measured using a penetrometer, which yields a composite measure of the tissue’s resistance to a combination of shear, tension, compressive and viscous forces. The penetrometer does not directly measure texture, but its simplicity has led to its widespread use. However, the test is destructive, resulting in the need for small samples to estimate the firmness of a population. Even if the quality of a population of fruit is judged acceptable for fresh consumption based on a tested sample, fruit-to-fruit variation can allow a large number of low-quality fruit to be packed and sold. Conversely, in a population of fruit considered substandard, a large portion of the fruit may actually be acceptable. Therefore, a nondestructive technology based on one or more of the attributes of quality for sorting the whole population is desirable to reduce losses and improve the quality of fruit delivered to the consumer.

Quality assessment by nondestructive measures of firmness has received much attention (Brown and Sarig, 1994). However, the rela-

tionship between firmness as perceived by the consumer and measures of firmness, such as elastic modulus, energy transfer, and proton magnetic resonance, has not been good enough to warrant widespread use of these technologies for apple.

Chlorophyll fluorescence has been used as a measure of chloroplast function and, indirectly, the physiological status of whole plants and plant organs. Fluorescence is induced by direct excitation of chlorophyll molecules of photosystem II (PSII) by light and their immediate relaxation. When PSII is functioning poorly, fluorescence characteristics are altered. Stresses such as chilling (van Kooten et al., 1992) and high temperature (Havaux et al., 1991) reduce PSII function. For banana (*Musa* sp., AAA group, Cavendish subgroup), chlorophyll fluorescence declines with ripening, probably due to chlorophyll loss and a loss in chloroplast competence (Smillie et al., 1987). Chlorophyll fluorescence has also been proposed as an indicator in stored apples of physiological disorders related to low O₂ and high CO₂ damage (DeEll et al., 1995).

These findings suggest that chlorophyll fluorescence might be used to detect differences in maturity, ripeness, or senescence of apple fruit. Fluorescence measurements are rapid (0.3 to 0.8 s) and can be made at some distance from the plant surface, thus permitting the use of a packingline-adaptive instrument. Our objectives were to measure changes in fluorescence during fruit maturation, ripening, and senescence, and to determine if there was a correlative relationship between chlorophyll fluorescence and quality indices of firmness and ground color.

Materials and Methods

Fruit. Three apple cultivars, ‘Starking Delicious’, ‘Law Rome’, and ‘Golden Delicious’, were selected for four studies to evaluate the effects of harvest maturity, refrigerated-air (RA) storage, RA vs. controlled-atmosphere (CA) storage, and poststorage holding conditions. The ‘Starking Delicious’ fruit used in the harvest maturity study were obtained from the Horticulture Teaching and Research Center of Michigan State Univ. The ‘Starking Delicious’ fruit used in the RA storage study, the ‘Law Rome’ fruit used in the CA/RA comparison study, and the ‘Golden Delicious’ fruit used in the post-CA holding study, were obtained from a commercial orchard in the Belding area of Michigan. The ‘Starking Delicious’ fruit used in the post-CA holding study were obtained from the Clarksville Horticultural Research Station of Michigan State Univ.

Harvest maturity (Expt. 1). ‘Starking Delicious’ fruit were harvested on 11 dates at 3-d intervals, beginning 24 Sept. 1994. On each date, 50 fruit were harvested and transported immediately to the laboratory. Once they had warmed to room temperature, 10 fruit were assessed for 1) internal ethylene levels using the method of Dilley and Dilley (1985), 2) fruit firmness, and 3) starch content using the method of Lau (1985). The data were inter-

Received for publication 29 July 1996. Accepted for publication 7 Feb. 1997. Research conducted at Dept. of Horticulture, Michigan State Univ. Mention of a trademark and proprietary product does not imply endorsement of the products named or criticism of similar ones not named. 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.

¹Postdoctoral Research Associate.

²Graduate Student.

³Associate Professor.

⁴Research Scientist.

puted according to Beaudry et al. (1993) with regard to harvest maturity. Ten additional fruit were used for fluorescence measurements both before and after holding for 6 d at room temperature. The remaining 30 fruit were held in RA storage at 0 °C for ≈ 200 d. The percentage of their surface covered with superficial scald was estimated after holding them for an additional 6 d at 22 °C.

RA storage (Expt. 2). About 200 'Starking Delicious' fruit were harvested on 27 Sept., 3 Oct., and 10 Oct. 1994, and transported immediately to the laboratory. On each date, 10 fruit were assessed for internal ethylene levels, fruit firmness, and starch content once they had warmed to room temperature (Lau, 1985). Fluorescence was measured on seven additional fruit. The remaining fruit were placed in RA storage at 0 °C, and seven fruit were removed at frequent intervals for ≈ 200 d. Fluorescence was measured on each date of removal from storage once fruit had warmed to room temperature, and again after an additional 3 and 6 d at 22 °C. After 90 d of RA storage, scald assessments were initiated. Scald was assessed as in the previous study.

Comparison of CA vs. RA fruit (Expt. 3). 'Law Rome' fruit were harvested in 1994 and stored at 0 °C under CA conditions (1.5% O₂, <3% CO₂) and under RA for 4.5 months. After storage, 192 and 169 fruit were randomly selected from several bins of CA- and RA-stored fruit, respectively. Fruit were warmed to 22 °C and fluorescence and firmness were determined. To investigate whether the degree of color interferes with fluorescence measurements, a subset of the CA-stored 'Law Rome' fruit were segregated into three color grades (<25% red; >25% red and <50% red; and >50% red), and fluorescence was measured on 10 fruits per grade. An analysis of variance (ANOVA) was performed and grade means separated using the least significant difference (LSD) procedure.

Poststorage holding (Expt. 4). 'Starking Delicious' and 'Golden Delicious' fruit were stored at 0 °C under two CA conditions (1.5% O₂, <3% CO₂ and 1.7% O₂, <3% CO₂, respectively) for 4.5 months in the 1994–95 season. Fruit of each cultivar were removed from storage, divided into two lots, and held at 22 °C. Holding periods were 18 d for 'Golden Delicious' and 19 d for 'Starking Delicious'. During the holding period, fruit were kept in ventilated, opaque, black plastic bags to avoid moisture loss and light effects. Two types of measurements were made, termed 'continuous' and 'discrete'. Continuous measurements were performed daily on the same seven fruit throughout the holding period; discrete measurements were made on a different set of five fruit every second day.

The purpose of the continuous measurements was to view changes in fluorescence on the same fruit and to reduce the effect of variation within a fruit population. The purpose of the discrete measurements was to permit destructive firmness measurements to be made and to relate changes in firmness with changes in fluorescence. Fruit firmness was regressed against Fv/Fm, Fo, and Fm and the

correlations tested for significance (Snedecor and Cochran, 1980). 'Golden Delicious' fruit were included in the study because their lack of red pigmentation permitted the measurement of background color changes. Hue angle of the discretely sampled fruit was regressed against Fv/Fm, Fo, and Fm and the correlations tested for significance (Snedecor and Cochran, 1980).

Firmness. The flesh firmness of fruit in the discrete measurement lots was evaluated manually using a drill stand-mounted Effegi penetrometer fitted with an 11.1-mm-diameter probe. The penetrometer was calibrated using a top-loading balance. Two disks (≈ 2.5 cm in diameter) of skin tissue were removed, one from the most highly colored side of the fruit and the second from the opposite surface. The penetrometer probe was pressed into the tissue to a depth of 8 to 9 mm in a single smooth motion requiring ≈ 1 to 2 s. Data were recorded in pounds and converted to N by multiplying by 4.45 N/lb.

Chlorophyll fluorescence. Fluorescence measurements were made in a darkened laboratory. Apple fruit were placed 4 mm from the end of the fiber optic light guide of a pulse-modulated fluorometer (model OS-500; Opti-Science, Tyngsboro, Mass.). The fluorometer was operated in the "Fv/Fm" mode and fluorescence was measured using a photodiode in the 710–760 nm range. During a run, minimal fluorescence (Fo) was monitored for 0.2 s at a rate of 100 readings per second (20 sample points). The excitation (modulated) light intensity (660 nm, with a filter for >700 nm light) for the Fo measurement was ≈ 0.15 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (OS-500 setting = 60), which was sufficient for accurate measurement of Fo (van Kooten and Snel, 1990). The addition of ≈ 3 mW (OS-500 setting = 50) of continuous, far red light (735 nm) did not influence fluorescence, therefore, we assumed that the redox components of the electron transport chain were fully oxidized. After Fo was determined, the sampling rate was increased to 1000/s and

Fig. 1. Effect of harvest date on starch index, Fv/Fm, percentage of fruit with greater than 0.2 $\mu\text{L}\cdot\text{L}^{-1}$ ethylene, and scald development following air storage for 'Starking Delicious' apple. Bars represent one standard deviation. Time between arrows indicates optimal harvest window based on maturity indices. Each data point represents an average of 10 fruit, except for the data for scald, where each data point represents 30 fruit.

a saturation light (660 nm) pulse was supplied via the light guide by a halogen lamp. The light intensity at the peel during the pulse was estimated to be $2400 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ photosynthetically active radiation (PAR) based on an OS-500 setting of 60; a setting of 255 yields $\approx 10,000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PAR. The pulse duration was 0.8 s, and a cutoff filter, blocking light above 700 nm, was used to prevent saturation of the photodiode. During the pulse, the maximum level of modulated chlorophyll fluorescence was designated as Fm. Three readings were taken at equidistant positions around the equator of each fruit and averaged. The efficiency of PSII (Fv/Fm) was calculated as (Fm-Fo)/Fm (van Kooten and Snel, 1990).

Skin color. Skin color of 'Golden Delicious' apple fruit was measured as lightness, chroma, and hue angle with a Minolta Chromameter 300 (Minolta Camera Co., Osaka, Japan). Color readings were made at three positions on each fruit and averaged. Only hue angle data were reported.

Results

Harvest maturity (Expt. 1). The internal ethylene concentration in 'Starking Delicious' fruit increased with time after the initial harvest date (data not shown), and the percentage of fruit with internal ethylene levels greater than $0.2 \mu\text{L}\cdot\text{L}^{-1}$ also increasing from 0% to 100% (Fig. 1). The starch index increased similarly from an average of 1.3 at the first harvest to 7.1 at the final harvest 30 d later (Fig. 1). Based on these data, the optimal harvest "window" for long-term CA storage was between 2 and 7 Oct., which is typical for this variety in the location in which it was obtained. Fluorescence parameters Fo and Fm declined with harvest date (data not shown). Fv/Fm at the time of harvest declined with harvest date, with the rate of decline increasing after the proportion of fruit with high levels of ethylene increased; a sharp decline occurred on the final harvest date (Fig. 1). The Fv/Fm measured 6 d after harvest was lower for those fruit harvested after the optimal storage window. Scald development after cold storage declined with harvest date.

RA storage (Expt. 2). Fv/Fm remained constant for the first 2 weeks of RA storage for 'Starking Delicious', then declined with time in a nearly linear fashion for each of the three harvest dates (Fig. 2). Fo and Fm declined in similar patterns (data not shown). When fruit were warmed to 22 °C, the rate of decline in Fv/Fm increased ≈ 10 - to 15-fold relative to that for fruit kept at 0 °C. Fv/Fm declined from an initial value of ≈ 0.78 for all harvests, to ≈ 0.6 for the first two harvests, and to 0.65 for the last harvest. Storage scald increased with time after 90 to 100 d of storage. The rate of scald development was most rapid for the first harvest and least rapid for the final harvest.

Comparison of CA vs. RA fruit (Expt. 3). Fluorescence, measured as Fv/Fm, was regressed against firmness for high-quality and low-quality fruit (Fig. 3A). The two populations appeared to segregate according to both firmness and Fv/Fm, but there was substan-

tially less overlap in the frequency distribution for Fv/Fm than in that for firmness. When Fv/Fm was used to segregate high-quality from low-quality fruit, the ratio of the percentage of correct segregates (accuracy) was at a maximum (75%) at Fv/Fm = 0.685 (Fig. 3B). At this threshold, $\approx 5\%$ of the low-quality fruit were wrongly categorized as high quality and $\approx 20\%$ of the high-quality fruit were categorized as low quality. On the other hand, the greatest accuracy for segregation based on firmness was only 55% when fruit softer than 49.5 N were categorized as low quality and firmer fruit were classified as high quality (data not shown). The fluorescence (Fv/Fm) of CA-stored 'Law Rome' fruit was not affected by the degree of skin coloration (data not shown).

Poststorage holding (Expt. 4). For continuously monitored fruit, Fo, Fm, and Fv/Fm declined with time in fruit for which continu-

ous measurements were taken (Fig. 4). The relative amount of change and the rate of change in fluorescence parameters of discretely measured fruit were similar (data not shown). For 'Starking Delicious' fruit, Fo declined from 180 to 120, Fm declined from 650 to 250, and Fv/Fm declined from 0.7 to 0.5 over the 19-d holding period. The decline in Fo and Fm began ≈ 2 to 4 d after moving the fruit to 22 °C. However, the decline in Fv/Fm was not apparent until 9 to 10 d after transfer to 22 °C. Changes in fluorescence followed a similar pattern for 'Golden Delicious' fruit; Fo and Fm decreased dramatically from 170 to 60, and 600 to 150, respectively, over the 18-d holding period (Fig. 4). Fv/Fm changed somewhat less for 'Golden Delicious' than for 'Starking Delicious', declining from 0.71 to 0.64. As for 'Starking Delicious', the decline in Fv/Fm appeared to begin several days after removal from storage.

Fig. 2. Effect of storage duration on Fv/Fm and scald development of 'Starking Delicious' fruit harvested 27 Sept., 3 Oct., and 10 Oct. and held at 0 °C. Open symbols represent fruit moved to 22 °C. Each data point represents an average of seven fruit.

Fig. 3. Fluorescence (F_v/F_m) and firmness for 'Law Rome' apple fruit following controlled-atmosphere (CA) (1.5% O_2 , <2.0% CO_2) or refrigerated-air (RA) storage for 4.5 months (A), and segregation success using F_v/F_m (B). Traces along Y-axis of 3A represent normalized frequency distributions of F_v/F_m for CA (solid line) and RA (dashed line) fruit. Traces along X-axis of 3A represent frequency distributions of firmness of CA (solid line) and RA (dashed line) fruit. Lines in 3B indicate percentage of RA fruit incorrectly identified as 'CA-stored' (dashed line) and of CA fruit incorrectly identified as 'RA-stored' (solid line), and accuracy (solid line with diamond symbols), which is the percentage of total fruit (RA and CA) that were correctly segregated.

The firmness of 'Starking Delicious' fruit decreased from ≈ 66 to 49 N (data not shown). Using an empirically derived nonlinear formula, firmness was correlated ($r^2 = 0.91$, $P < 0.01$) with F_v/F_m (Fig. 5). The decline in F_m was also correlated with firmness loss, but the relationship was linear ($r^2 = 0.92$, $P < 0.01$). F_o was also linearly correlated ($r^2 = 0.6$, $P < 0.05$) with firmness (Fig. 5). 'Golden Delicious' fruit underwent a much less marked decline in firmness than 'Starking Delicious', decreasing with time from 57 to 51 N (data not shown). Firmness for 'Golden Delicious' fruit did not change with F_v/F_m , with a correlation coefficient of 0.67 ($P > 0.05$) using the same nonlinear formula as for 'Starking Delicious' (data not shown). F_o and F_m linear regressions were similarly nonsignificant (data not shown).

Hue angle decreased from $\approx 110^\circ$ to 95° as visible color changed from light-green to full-yellow for continuously and discretely sampled fruit (Fig. 6). Skin color was linearly correlated with both F_m ($r^2 = 0.93$, $P < 0.01$) and F_o ($r^2 = 0.85$, $P < 0.01$) for the discretely sampled fruit (Fig. 5). Similar results were obtained for the continuously monitored fruit (data not shown).

Discussion

Chlorophyll fluorescence is used by photobiologists to investigate photosynthetic reactions (Mishra and Singhal, 1992; van Kooten and Snel, 1990) and has, more recently, been widely used by plant physiologists and breeders to reveal physiological stress and to identify stress-resistant selections (Schreiber and Bilger, 1993). Collectively, studies on chlorophyll fluorescence indicate that it is a helpful

tool for investigating physiological activities of plants. Of particular interest to the fresh produce industry is its potential to rapidly and nondestructively measure product quality.

There is general agreement that membrane deterioration is a fundamental aspect of senescence that is initiated early in the senescence process (Meir et al., 1992; Thompson, 1988). While the chloroplast membranes retain their physical integrity until late in senescence,

photosynthetic capacity declines from the earliest stages of senescence (Gepstein, 1988). Hariyadi and Parkin (1991) demonstrated that destruction of PSII is related to the peroxidative decay of cell membranes. Thus, the decline in chloroplast function parallels the decline in more global aspects of plant organ senescence. For apple fruit, this suggests that firmness, color, and fruit flavor, which undergo time- and temperature-dependent changes following harvest (Brackmann et al., 1994; Knee et al., 1972; Lau, 1985), should be accompanied by time- and temperature-dependent changes in chloroplast function and capacity as occur for ripening banana (Smillie, et al., 1987) and chilled cucumber (*Cucumis sativus* L.) and pepper (*Capsicum annuum* L.) fruit (Tijksens et al., 1994).

Changes in indices of ripening and senescence that we measured were correlated with declines in fluorescence parameters F_o , F_m and F_v/F_m , suggesting a relationship between fluorescence and the level of fruit senescence. The drop in F_v/F_m for fruit with higher starch index and ethylene content at harvest, which were typical of ripening fruit (Knee et al., 1989), supports the possibility of the fluorescence changes in apple being ripening- and senescence-related. Further support is derived from the fact that advanced maturity at harvest reduces storage scald. In this research, susceptibility to storage scald was less for fruit having a lower F_v/F_m at harvest and 6 d following harvest. In addition, the development of scald during RA storage, which occurs only in ripe, aging fruit, took place only for fruit for which F_v/F_m had declined considerably after harvest, again suggesting a link between chlorophyll fluorescence and senescence. Moreover, the decline in fluorescence during RA storage is certainly consistent with expected changes in fruit senescence, as is the accelerated drop

Fig. 4. Decline in chlorophyll fluorescence parameters for five continuously monitored 'Starking Delicious' (solid symbols) and 'Golden Delicious' (open symbols) apple fruit at 22 °C in air following removal from controlled-atmosphere storage (4.5 months at 1.5% O_2 , <2.0% CO_2).

Fig. 5. Relationship between fluorescence parameters and firmness for 'Starking Delicious' apple fruit following removal from controlled-atmosphere (CA) storage (4.5 months at 1.5% O₂, <2.0% CO₂). Each data point represents seven fruit. Lines represent best fit curvilinear equations. Bars represent $\pm$ SE.

in fluorescence when fruit were moved to a higher temperature. Interestingly, the fruit that declined the least in Fv/Fm (10 Oct. harvest) developed the least severe scald.

The loss in greenness as fruit ages is often used as an indicator of maturity, senescence, or both (Kingston, 1992). The change in apple fruit color is a result of chlorophyll loss and, to a limited degree, carotenoid accumulation (Knee, 1972). Fo is dependent upon the amount of light chlorophyll emits under illumination that does not induce O₂ generation, and reflects a combination of both chloroplast function and relative chlorophyll content. The strong correlations found between color and Fm imply that fruit background color and fluorescence are related physiologically. This supposition is consistent with the findings of Smillie et al. (1987), who reported fluorescence during ripening of banana fruit at 20 °C as a result of loss in chlorophyll content and a decrease in photosynthetic competency per unit chlorophyll. One must caution, however, against presuming that changes in Fo or Fm are due to changes in chlorophyll content alone, since a number of stresses can alter these readings (Tijskens et al., 1995; van Kooten et al., 1992; Woolf and Liang, 1996). Abbott (1994) commented that fluorescence measurements for predicting chilling injury in eggplant (*Solanum melongena* var. *esculentum* Ness.) were limited by high concentrations of pigments. However, our finding that the blush or red coloration of apple did not interfere with fluorescence readings suggests that the same may not be true for apple.

The concept that fluorescence measurements can, to some extent, reflect the degree of fruit senescence is further strengthened by the

correlative relationship of Fv/Fm to firmness for 'Starking Delicious' fruit. Fluorescence measurements are made from chlorophyll-containing tissue in the upper few cell layers, which are removed for firmness determination. If the decline in fluorescence were not synchronous with other aspects of tissue degradation such as tissue softening, one would

not necessarily expect a decline in firmness to be correlated with a decline in chlorophyll fluorescence. The relatively poor relationship between the firmness and chlorophyll fluorescence in 'Golden Delicious' may, in part, be due to the initially low firmness of these fruit or may reflect cultivar variation in the pattern of change in chloroplast competency.

The findings relating fluorescence and firmness and background color for 'Starking Delicious', 'Golden Delicious', and 'Law Rome' fruit suggest that chlorophyll fluorescence may be of some use as a tool to estimate fruit quality or condition. However, the amount of fruit-to-fruit variation within a population in the study segregating high- and low-quality fruit is of some concern. The minimal 25% error rate reported here, while lower than that for firmness, may not be acceptable in an industry where low profit margins are typical. A number of additional issues have yet to be resolved regarding the use of fluorescence for condition assessment, either during a sorting process or for product monitoring. Cultivar, temperature, and storage atmosphere effects on the relationship between chlorophyll fluorescence and firmness, mealiness, flavor, and other quality attributes, need to be determined. Furthermore, physically accomplishing the task of fluorescence measurement prior to sorting apple fruit may pose a challenge for commercial implementation. Although fluorescence parameters can be collected within 1 s/fruit, fruit throughput on packing lines is usually 10 fruit/s. Use of this technology may rely on improving measurement techniques and/or sorting algorithms that take into account more than one fluorescence parameter. Alternatively, coupling fluorescence equipment with another complementary, nondestructive technology

Fig. 6. Changes in skin color of 'Golden Delicious' apple fruit held at 22 °C in air following removal from controlled-atmosphere (CA) storage (4.5 months, 1.5% O₂, <2.0% CO₂). Open symbols represent discrete samples (n = 7) and solid symbols represent continuously monitored fruit (n = 5). Inset: Correlation between skin hue angle and measurements of minimal fluorescence (Fo) (Fo = 11094 + 11.8 × hue angle, r² = 0.85, P < 0.01), and maximal fluorescence (Fm) (Fm = -4314 + 45.4 × hue angle, r² = 0.93, P < 0.01). Bars represent $\pm$ SE.

might be helpful. Despite possible shortcomings, fluorescence may have some potential for sorting systems and warrants further investigation for use for apple and other chlorophyll-containing commodities.

Literature Cited

- Abbott, J.A. 1994. Temperature damage measurement by fluorescence or delayed light emission from chlorophyll, p. 44–49. In: G.K. Brown and J. Sarig (eds.). ASAE 05-94. Proc. Intl. Workshop of Nondestructive Tech. Qual. Eval. Fruits and Veg., Amer. Soc. Agr. Eng., St. Joseph, Mich.
- Beaudry, R.M., P. Schwallier, and M. Lenington. 1993. Apple maturity prediction: An extension tool to aid fruit storage decisions. *HortTechnology* 3:233–239.
- Brackmann, A., J. Streif, and F. Bangerth. 1993. Relationship between a reduced aroma production and lipid metabolism of apples after long-term controlled atmosphere storage. *J. Amer. Soc. Hort. Sci.* 118:243–247.
- Brown, G.K. and J. Sarig. 1994. ASAE 05-94. Proc. Intl. Workshop of Nondestructive Tech. Qual. Eval. Fruits and Veg., Amer. Soc. Agr. Eng., St. Joseph, Mich.
- DeEll, J.R., R.K. Prange, and D.P. Murr. 1995. Chlorophyll fluorescence as an indicator of low O₂ or high CO₂ stress in apples during storage. *HortScience* 30:1058–1059.
- Dilley, C.L. and D.R. Dilley. 1985. New technology for analyzing ethylene and determining the onset of ethylene climacteric in apples. Proc. 4th Natl. Controlled Atmos. Res. Conf., Raleigh, N.C., 23–26 July 1980.
- Dull, G.G. and A.C. Hulme. 1971. Quality, p. 721–725. In: A.C. Hulme (ed.). *The biochemistry of fruit and their products*. vol. 2. Academic, New York.
- Gepstein, S. 1988. Photosynthesis, p. 85–109. In: L.D. Nooden and A.C. Leopold (eds.). *Senescence and aging in plants*. Academic, New York.
- Hariyadi, P. and K.L. Parkin. 1991. Chilling-induced oxidative stress in cucumber fruits. *Postharvest Biol. Technol.* 1:33–45.
- Havaux, M., H. Greppin, and R.J. Strasser. 1991. Functioning of photosystems I and II in pea leaves exposed to heat stress in the presence or absence of light. *Planta* 186:88–89.
- Kingston, C.M. 1992. Maturity indices for apple and pear. *Hort. Rev.* 13:407–432.
- Knee, M. 1972. Anthocyanin, carotenoid and chlorophyll changes in the peel of Cox's Orange Pippin apples during ripening on and off the tree. *J. Expt. Bot.* 23:184–196.
- Knee, M., S.G.S. Hatfield, and S.M. Smith. 1989. Evaluation of various indicators of maturity for harvest of apple fruit intended for long-term storage. *J. Hort. Sci.* 64:403–411.
- Lau, O.L. 1985. Harvest indices for B.C. apples. *BC Orchardist* 7:1a–20a.
- Lovelidge, B. 1987. A penetrating assessment of fruit firmness. *Grower* 108:53–54.
- Meir, S., L. Rubin, G. Zauberman, and Y. Fuchs. 1992. Changes in fluorescent lipid peroxidation products of room-ripened and vine-ripened tomato fruits in relation to other ripening parameters. *Postharvest Biol. Tech.* 2:125–135.
- Mishra, R.K. and G.S. Singhal. 1992. Function of photosynthetic apparatus of intact wheat leaves under high light and heat stress and its relationship with peroxidation of thylakoid lipids. *Plant Physiol.* 98:1–6.
- Schreiber, U. and W. Bilger. 1993. Progress in chlorophyll fluorescence research: Major development during the last years in retrospect. *Prog. Bot.* 54:151–173.
- Smillie, R.M., S.E. Hetherington, R. Nott, G.R. Chaplin, and N.L. Wade. 1987. Applications of chlorophyll fluorescence to the postharvest physiology and storage of mango and banana fruit and the chilling tolerance of mango cultivars. *Asian Food J.* 3:55–59.
- Snedecor, G.W. and W.G. Cochran. 1980. *Statistical methods*. 7th ed. Iowa State Univ. Press, Ames.
- Thompson, J.E. 1988. The molecular basis for membrane deterioration during senescence, p. 51–83. In: L.D. Nooden and A.C. Leopold (eds.). *Senescence and aging in plants*. Academic, New York.
- Tijskens, L.M.M., E.C. Otma, and O. van Kooten. 1995. Photosystem II quantum yield as a measure of radical scavengers in chilling injury in cucumber fruits and bell peppers. *Planta* 194:478–486.
- van Kooten, O., M.G.J. Mensink, E.C. Otma, A.C.R. van Schaik, and S.P. Schouten. 1992. Chilling damage of dark stored cucumbers (*Cucumis sativus* L.) affects the maximum quantum yield of photosystem 2, p. 161–164. In: N. Murata (ed.). *Progress in photosynthesis research*. vol. IV. Kluwer Acad. Publ., Dordrecht, The Netherlands.
- van Kooten, O. and J.F.H. Snel. 1990. The use of chlorophyll fluorescence nomenclature in plant stress physiology. *Photosyn. Res.* 25:147–150.
- Woolf, A.B. and W.A. Liang. 1996. Avocado fruit skin fluorescence following hot water treatment and pretreatment. *J. Amer. Soc. Hort. Sci.* 121:147–151.