Air Temperature and Illumination During Transportation Affect Quality of Mature Tomato Seedlings

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Abstract. Increasing numbers of greenhouse vegetable growers purchase transplants from specialized transplant propagators. Possible deterioration of transplants during transportation limits the market size as well as the potential sources of high-quality transplants. To determine the best conditions for transportation of seedlings, tomato (*Lycopersicon esculentum* Mill., cv. Durinta) seedlings with visible flower trusses were placed for 4 days inside growth chambers to evaluate the effects of short-term exposure to different air temperatures (6, 13, or a conventional transportation temperature of 19 °C) under darkness or illumination at 12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF. Plants were evaluated for visual quality, photosynthetic ability, growth, and fruit yield. Lower temperatures and illumination significantly maintained visual quality of the seedlings. Lower temperature maintained high photosynthetic ability of seedlings during the 4-day treatment. After transplanting in the greenhouse, a significant number of trusses exhibited flower abortion or delayed fruit development when seedlings were treated at 19 °C regardless of light intensity. Results suggested that 6 to 13 °C was the best transportation temperature for up to 4 days, which was later validated by an actual transportation trial between British Columbia and Arizona.

Production of high-quality transplants is crucial to support the success of final crop production both in open fields and greenhouses. Organizational separation of transplant production from the final crop production is a recent worldwide trend, especially for vegetable and floriculture crops that require special techniques such as grafting or vegetative propagation and unique facilities to produce desirable transplants. There is a growing nationwide interest in use of high-quality grafted seedlings for greenhouse tomato production, whereas sources of grafted tomato seedlings are still limited in the United States. Consequently, greenhouse tomato growers often purchase grafted seedlings from distant propagators risking deterioration of transplants during transportation and subsequent delayed growth or fruit development. Transportation conditions, status of the flower development at the time of transportation, planting con-

ditions after transportation, and unfavorable combinations of these conditions often resulted in flower abortion and delayed fruit development of the first truss (Kubota et al., 2004). However, mechanisms of flower abortion and delayed fruit development were left undefined, and therefore significant yield loss and delay were often experienced.

Distance of transportation is a limitation for propagators to reach customers and also for growers to select possible sources of seedlings. Optimization of transplant transportation can contribute to maintaining quality of seedlings of specialty crops, whose sources are limited and must be transported long distances.

Transplant quality deteriorates quickly when stored at an ambient temperature under darkness. Combinations of low temperatures and dim light levels (1–5 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF, depending on plant species and temperature) have been shown to extend storability of young transplants of various floricultural and vegetable crops without inducing deterioration such as succulent elongation, leaf yellowing, or wilting (Heins et al., 1992; Kubota, 2003; Kubota et al., 2002). Environmental conditions during transportation can theoretically affect the quality of transplants and thereby yield and quality of the final products originating from the transplants.

Among limited research, several reports focused on optimum and economic means to transport seedlings long distances. Research has been conducted toward containerized tomato seedling transportation for field growers (e.g., Leskovar and Cantliffe,

1991). Risse and Moffitt (1984) examined various types of containers for transporting and storing bare-rooted young tomato seedlings. Handling of young tomato seedlings, storage duration (up to 8 d), and storage temperature (5 and 15 °C) reportedly affected seedling morphology and yield (Leskovar and Cantliffe, 1991). The plants used in the past reports are generally younger and smaller than those mature seedlings that greenhouse hydroponic growers prefer (6–8 weeks old, 15–20 cm height often with visible flower trusses), because introducing mature seedlings in greenhouse reduces the time to first harvest, particularly when “interplanting.” Interplanting is a common greenhouse tomato production technique of planting seedlings among old finishing plants (Peet and Welles, 2005) to allow continuous year-round production. However, there is practically no information on how transportation conditions affect such mature tomato seedlings with visible flower trusses. Analysis of the factors affecting transportability of mature tomato seedlings is important, and optimization of transportation conditions will enhance further development of greenhouse tomato and specialty crop industries. The objective of the present study was to examine effects of air temperature and illumination during transportation on visual quality, photosynthetic ability, and early yield of mature tomato seedlings.

Materials and Methods

Seedling growth conditions. ‘Durinta’ (Western Seed Americas, Westport, Conn.) tomato seedlings (seeded on 20 Feb 2003 and 20 Apr 2004) were grown in rockwool cubes (10 cm W × 10 cm D × 6.5 cm H) in a University of Arizona greenhouse (Tucson, Ariz.) with a pad-and-fan evaporative cooling system and an overhead natural gas heating system (24 and 18 °C day and night air temperature settings, respectively). Seedlings were prepared to have two axillary shoots per plant by pinching the shoot tip 3 weeks after seeding. To promote the flower bud development, the nighttime temperature setting was reduced to 15 °C during the first experiment (Mar.–Apr. 2003), and the seedlings were kept in a temperature-controlled growth chamber (15 °C) every night from 10 PM to 8 AM during the second experiment (May to June 2004).

Four to 5 weeks after pinching (24 Apr 2003 and 11 June 2004), the seedlings reached transplanting size (seven true leaves, 20–22-cm stem length) with visible first flower truss (9–15-mm truss size) and they were randomly divided (16 seedlings per treatment) and subjected to one of three air temperatures (6, 13, or 19 °C) combined with two light intensities (darkness or 12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF) inside growth chambers for 4 d. The treatment at 19 °C in darkness approximates the conventional transportation conditions practiced in the long distance transportation between Canadian propagators and U.S. hydroponic tomato growers (Kubota

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et al., 2004). Duration of the treatment was 4 d, the current maximum duration of transportation used by commercial propagators (Bevo Farms, August 2002, personal communication). Other conditions (relative humidity, plant density, and air exchange of the container) were set as close as possible to the actual transportation environment assessed from a 2-d transportation of seedlings from British Columbia, Canada, to Arizona (Kubota et al., 2004). The only environmental condition that was not simulated was road vibration that may possibly cause mechanical stress to seedlings. During the 4-d treatment, additional 16 seedlings were left in the greenhouse and grown without treatment as the control. After 4 d, seedlings were taken from the chambers and transplanted into 7.6-L pots filled with a commercial substrate (Sunshine Mix #1; Sun Gro Horticulture, Bellevue, Wash) in the greenhouse (day/night set point at 24/18 °C). Transplanting was completed during early morning hours to minimize potential transplanting shock as practiced in a commercial greenhouse operation. All seedlings were grown in a high-wire system for 3 months. Drip irrigation was applied with a tomato hydroponic nutrient solution containing N-NO₃, P, K, Ca, and Mg at 189, 39, 341, 170, and 48 mg·L⁻¹ and other micronutrients (Jensen and Rorabaugh, January 2003, unpublished data) at a rate of 100 mL per plant every 15 to 18 min (adjusted according to the transpiration demand) starting from 6 AM and continuing to 7 PM. This irrigation procedure is common in aggregate hydroponics so as to maintain 30% to 40% efflux of the nutrient solution (Jensen, personal communication). Common greenhouse plant maintenance, including leaf pruning and removing side shoots, was conducted on a weekly basis. Pests were controlled biologically, periodically introducing parasitic wasps (*Encarsia formosa* Gohan) for whitefly (*Trialeurodes vaporariorum* Westwood) and applying sulfur dust for russet mites (*Aculops lycopersici* Massee). Flowering trusses were vibrated for 1 s every other day using an electric pollinator to promote pollination.

Growth chamber treatment conditions. Three identical growth chambers (model 2015; VWR, West Chester, Penn) were used for creating a 6, 13, or 19 °C air temperature. Two acrylic boxes (44 cm W, 54 cm D, 41 cm H) ("storage chamber" hereafter), each with 16 seedlings, were placed in each growth chamber. The lower storage chamber was entirely covered with double layers of black plastic sheeting to prevent light transmission. The upper storage chamber was placed under white fluorescent lamps to provide 12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF on the plant canopy level inside the storage chamber. Sides of the lighted chamber were covered with the same black plastic sheeting to prevent light entering from the side of the seedling canopy. All storage chambers were sealed after placing the seedlings inside to limit the ventilation during the treatment. A standalone temperature and relative humidity

sensor (HOBO Pro RH/Temp; Onset Computers, Bourne, Mass.) was placed inside each storage chamber to monitor the internal environment conditions. The sensors were manufacturer-calibrated before use. A small fan (0.015 m³·s⁻¹) was placed inside each growth chamber to minimize temperature differences (<0.5 °C) between upper (lighted) and lower (dark) chambers.

Measurement and analysis. One day before and after the 4-d treatment, stem length was recorded for each seedling. Net photosynthetic rate of fully expanded young leaves was measured 1 d after the removal of seedlings from the treatment using a leaf gas exchange measurement system (CIRAS2; PPSystems, Amesbury, Mass.) to evaluate the photosynthetic ability of seedlings. The leaf gas exchange chamber was set at 400 $\mu\text{mol}\cdot\text{mol}^{-1}$ CO₂ concentration and 24 °C air temperature under 1500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF provided by a halogen lamp system (PPSystems).

Ethylene and CO₂ concentrations of head space inside the storage chambers were measured after 3 d of the treatment (1 d before the removal of seedlings). Ten milliliters of gas was sampled from each chamber using airtight syringes, and the ethylene concentrations were analyzed using a gas chromatograph (model GC14; Shimadzu, Kyoto, Japan). For CO₂ concentration measurement, the CIRAS2 IR gas analyzer (IRGA) was connected to each storage chamber and air was circulated for a few minutes at a rate of 0.5 L·min⁻¹ within the closed circuit created with the storage chamber and the IRGA.

Two weeks after transplanting, plant stem length and number of leaves were recorded to compare early growth and development of seedlings as affected by treatment conditions. Three weeks after transplanting, incidences of normal and abnormal fruit set were recorded for first and second trusses. Fruits were pruned to five fruits per truss 4 weeks after transplanting and harvested as they reached the red ripe stage. Harvest date and yield were recorded for the first and second trusses.

Experimental design and statistical analysis. The experiment was conducted twice with completely randomized designs. The first experiment was from Feb. to July 2003 and the second experiment was from Apr. to Aug. 2004 with minor differences in seedling preparation as described here. Statistical analysis of main factor effects, interactions, and mean separation was applied using JMP software (SAS Institute, Cary, N.C.).

Results and Discussion

Greenhouse and growth chamber environments. Daily average, maximum and minimum air temperature after transplanting in the greenhouse were 22 ± 1.0, 27 ± 1.7, and 18 ± 1.3 °C during the 2003 experiment and 25 ± 1.1, 29 ± 1.4, and 21 ± 2.5 °C during the 2004 experiment, respectively. Air temperature inside storage chambers was at 6 ± 0.3, 13 ± 0.3, or 19 ± 0.3 °C during the 4-d storage

treatment in both experiments. Relative humidity inside the chambers was almost 100% regardless of temperature. Although there were differences in greenhouse environments and plant growth rates between two years, no interactions were observed for the factors of air temperature, illumination, and year.

Seedling growth during simulated transportation. During the 4-d treatment, all stems experienced succulent elongation of 15% to 43% with the greatest stem elongation at 19 °C in darkness (Fig. 1). Significant suppression of stem elongation under illumination was observed at 19 °C, but not at 6 or 13 °C. A similar response was observed in broccoli seedlings in which they elongated more at 10 °C and 15 °C than at 5 °C and also more in the dark than under 2 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF (Kubota and Kozai, 1995). The 47% stem elongation in the control seedlings was the result of normal growth in greenhouse rather than succulent elongation, whereas growth and development of the stored seedlings were temporarily suppressed by the treatment conditions. Stem length is considered as an important morphologic characteristics relating to the overall quality of transplants. Growers prefer strong-looking seedlings with short internodes rather than elongated seedlings, although the actual impact of such morphologic characteristics on yield is not well quantified.

Visual quality and photosynthetic ability of the seedlings. One week after transplanting, some seedlings, especially when stored for 4 d in the dark or at higher air temperature, exhibited necrosis and chlorosis on leaves, possibly associated with photoinhibition induced by transition from dark environment into the bright and warm greenhouse environment. Thirty-eight percent to 44% of seedlings treated at 19 °C exhibited necrosis or chlorosis, whereas only 6% to 12% of seedlings treated at 6 or 13 °C under illumination did (data not shown). The degree of damage on leaves was more pronounced when seedlings were in darkness than in light.

Air temperature during the treatment also affected net photosynthetic rate (NPR) measured 1 day after transplanting, whereas light did not (Fig. 1). Seedlings treated at 19 °C had the lowest NPR, whereas those treated at 6 °C had the greatest NPR, which was as high as that in the control. Lowering temperature was also reported to retain photosynthetic ability of broccoli (Kubota and Kozai, 1995), eggplant (Kozai et al., 1996), and tomato (Fujiwara et al., 1999) during 2 to 6 weeks of storage. Mena-Petite et al. (2003) reported that bare root and soil plug pine seedlings stored at 4 °C exhibited greater net photosynthesis, leaf water potential, chlorophyll a fluorescence parameters, survival percentage on transplanting, and root growth after transplanting than did those stored at 10 °C.

Effects of storage air temperature and illumination on young seedlings have been well investigated. Heins et al. (1995) reported that young tomato seedlings were susceptible to chilling injury at 5 °C or less. Storage air temperature for tomato seedlings is reportedly

Fig. 1. Effects of air temperature (6, 13, and 19 °C) and illumination (12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF) during 4-d storage treatment to simulate transportation on stem elongation (percent increase) and net photosynthetic rate (NPR) per leaf area of tomato seedlings. Means with standard errors are shown. Means with the same alphabetical letter are not significantly different by Turkey HSD test at $P < 0.05$. Means with a single asterisk (*) are not significantly different from the nontreated control by Dunnett's test at $P < 0.05$. NPR were measured 1 d after removal from the treatment at 1500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF, 400 $\mu\text{mol}\cdot\text{mol}^{-1}$ CO_2 concentration and 24 °C air temperature. Effect of illumination on NPR was nonsignificant.

recommended as 10 to 13 °C for less than 10 d (Leskovar and Cantliffe, 1991), whereas others stated that tomato seedlings can be stored at 7.5 °C for 3 weeks (Gross et al., 2002; Heins et al., 1995). When stored at 10 °C in darkness, tomato seedlings did not exhibit any notable changes in visual quality for up to 7 d (Fujiwara et al., 2001). Illumination during our 4-d treatment to simulate transportation did not affect the photosynthetic ability of the plants, whereas dim light (2–3 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was shown to maintain photosynthetic ability of broccoli seedlings stored at 5 to 10 °C for 6 weeks (Kubota and

Kozai, 1995) and to improve storability of young tomato plug seedlings stored at 10 °C for 2 weeks (Fujiwara et al., 2001). Effects of illumination can be more pronounced for a longer duration of transportation or storage than the 4 d tested in the present experiment.

Gaseous environment inside the storage chamber during the treatment. Carbon dioxide concentration measured after 3 d in the storage chamber was greater than 9999 $\mu\text{mol}\cdot\text{mol}^{-1}$, our quantification limit by IRGA based measurement, regardless of air temperature or light intensity. This means that the 12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF was lower than the

light compensation point of the seedlings. Ethylene was measured for the second year only and was detected inside the storage chamber in all treatments. Higher air temperature during the treatment significantly increased the ethylene concentration (47 ± 11 , 86 ± 15 , and 118 ± 10 $\text{nmol}\cdot\text{mol}^{-1}$ at 5, 13, and 19 °C, respectively). Illumination did not significantly affect the ethylene accumulation.

In the present experiment, mechanical stress incited by vibration during transportation was not simulated during the 4-d treatment using growth chambers. Excessive mechanical stress during transportation reportedly suppressed root growth of pine seedlings (Stjernberg, 1996) in which various vehicle types and resulting mechanical stresses were compared. Mechanical stress could also negatively impact seedling growth and development, because it could enhance ethylene production (Abeles et al., 1992; Beyl and Mitchell, 1983). Ethylene production in actual transportation will be also affected by road surface conditions. Stjernberg (1996) reported that there were 10 times more mechanical shocks with greater peak acceleration force when transported on gravel roads than on paved roads. Further investigation is necessary for effects of mechanical stress on the accumulation of ethylene inside the trailer during transportation.

Plant growth and development of the first and second truss. Stem length and number of leaves recorded 2 weeks after the treatment did not show significant difference among treatments (data not shown). Three weeks after transplanting, the first truss developed fruits of 2 to 3 cm in diameter. Number of fruits was significantly lower when seedlings were treated at 19 °C, regardless of light, but not significantly different from that in the control when treated at lower air temperatures (Table 1). Normal fruit development proceeds from proximal to distal end of the truss, resulting in the largest fruits at the proximal end and the smallest fruits at the distal end. Thirty-three percent of plants treated at 19 °C aborted flowers or showed delayed fruit development at the proximal end of first truss (only 66% showed normal truss development), as shown in Fig. 2. Control plants did not show any flower abortion or abnormal fruit development (100% normal, Table 1). The plants treated at 6 and 13 °C showed a low incidence of flower abortion or delayed fruit development on the first truss, but these values were not significantly different from the control treatments. Illumination during the 4-d treatment significantly improved development of the first trusses (Table 1). The percent normal first truss was 8.4% greater under illumination compared with those in the dark. No abortion or delayed fruit development was observed for the second truss in all treatments (data not shown).

Possible factors inducing flower abortion and delayed fruit development observed in the present experiment are 1) ethylene accumulation and 2) altered sink–source relationship during the storage. Ethylene is generally

Table 1. Effects of air temperature and illumination ($12 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPF) during 4-d storage treatment to simulate transportation on development and yield of the first trusses.^z

Treatment factors	No. of fruit set before pruning		Percent normal truss		Days from transplanting to harvest		Truss yield (g per truss)		Fruit size (g)	
	Means ^x	Comparison with control ^w	Means ^x	Comparison with control ^w	Means ^x	Comparison with control ^w	Means ^x	Comparison with control ^w	Means ^x	Comparison with control ^w
Air temperature ^y	0.0001		0.0001		0.0001		0.0001		0.0001	
6	6.7 A	NS	99 A	NS	59 B	NS	451 A	NS	93 A	NS
13	6.9 A	NS	96 A	NS	60 B	NS	413 A	NS	86 A	NS
19	5.8 B	*	66 B	*	63 A	*	339 B	*	75 B	*
Lighting ^y	0.871		0.030		0.484		0.302		0.516	
Light	6.5	NS	90 A	NS	60	NS	410	NS	86	NS
Dark	6.5	NS	83 B	*	61	*	393	NS	84	NS
Interaction (AT $\times$ L) ^y	0.845		0.641		0.056		0.866		0.968	
Control	6.8		100		58		401		83	

^zNumber of fruit set and percentage of normally developed trusses were observed after 3 weeks of transplanting (fruit pruning were performed after 4 weeks).

^yMain factors and its interaction probabilities analyzed by linear model analysis.

^xMeans followed by the same letter (A or B) are not significantly different by Turkey HSD test at $P < 0.05$.

^wMean comparison with the control treatment by Dunnett's test at $P < 0.05$.

^{NS}Nonsignificant, *Significant.

Fig. 2. Tomato truss showing delayed proximal fruit development (left) when treated at 19 °C air temperature for 4 d as a comparison with a normal truss (right). Proximal truss end normally supports the largest developing fruits (right), but the truss in left has the largest fruits in the middle of the truss as a result of the abnormal development in the proximal fruits.

known to affect flower abortion (Abeles et al., 1992). Temperature and light generally affect ethylene production and ethylene sensitivity of plants (Klassen and Bugbee, 2004). Increasing temperature reportedly increased ethylene production using bean leaf disk as a model system (Field and Barrowclough, 1989), and tobacco plants in darkness produced more ethylene than in light (Gepstein and Thimann, 1980). In the present study, higher ethylene concentration was observed at higher air temperature inside the storage chamber, suggesting that ethylene production rate of plants increased with increasing temperature. However, there is a limited amount of information regarding threshold values of acute and prolonged exposure that cause adverse effects such as flower abortion. The large difference in flower abortion between 13 °C and 19 °C may indicate that the threshold ethylene concentration for causing

flower abortion in the present experiment existed between the levels observed at two temperatures (86 and 118 $\text{nmol}\cdot\text{mol}^{-1}$ at 13 and 19 °C, respectively). Further investigation is necessary to evaluate ethylene involvement in flower abortion after long distance transportation by using an ethylene reaction inhibitor.

The high CO_2 concentrations inside the storage chamber observed in our experiment indicated that the light intensity inside the storage chamber ($12 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was too low to maintain the dense seedling canopy under positive carbon balance during the 4-d treatment. Influence of illumination might be more pronounced at a higher light intensity, although installing lighting systems with higher output inside moving trailers may not be practical. Placing seedlings at higher temperatures, especially in the dark, reduces soluble solid sugar concentrations (Kubota

et al., 1997). Sink-source relationship and competition over photoassimilates among sink organs are well-known concepts in crop physiology. According to Ho (1988), the highest sink strength in young flowering tomato plants is in the roots followed by leaves. Inflorescences are considered the weakest sink organ for young tomato seedlings (Ho, 1988), and environmental conditions that cannot provide enough photoassimilates may cause abortion of inflorescences. In commercial tomato greenhouses, seedlings that underwent long distance transportation were held in the greenhouse without transplanting to temporarily prevent vigorous root growth into the rooting media allowing photoassimilates to be allocated to the flower truss (Jensen, personal communication). During the 4-d treatment, tomato seedlings probably had a greater respiration rate at higher temperature conditions and in the dark than in the light. This may have caused consumption of carbohydrate reserves and reduced allocation of carbohydrate to the flowering truss, and caused flower abortion and delayed fruit development.

Yield of the first and second truss. The first truss was harvested at an average of 58 d after transplanting in the control treatment, whereas it was 63 d after transplanting, delayed by nearly a week, when treated at 19 °C in the storage chamber (Table 1). Illumination during the 4-d treatment did not significantly affect the days to harvest. No significant delay in harvest was observed when treated at 6 or 13 °C compared with the control treatment. The second truss harvest timing did not show significant delay, regardless of treatment (data not shown).

The first truss yield was reduced by 15% and individual fruit size was reduced by 10%, as compared with the control treatment, when plants were treated at 19 °C (Table 1). Treatment at 6 or 13 °C did not affect yield nor fruit size significantly. Illumination in storage did not affect the first truss yield or individual fruit size. Second truss yield was unaffected by the treatment regardless of

conditions (data not shown), which was in agreement with what was observed in commercial greenhouses. A separate experiment also confirmed that storage or transportation conditions did not affect fruit development and yield of the trusses that were undeveloped (or not visible) at the time of storage or transportation. This explains why the treatment effect was significant in the first trusses but not in the second trusses, because the second flower trusses were not visible when the treatment was applied.

Overall, exposure of the mature tomato seedlings to 19 °C under darkness or illumination for 4 d exhibited serious quality deterioration of seedlings, flower abortion, delay in fruit development on the first truss, and yield reduction. Illumination in storage improved the first truss development by reducing the incidence of flower abortion and delayed fruit development. Lowering air temperature to 6 or 13 °C maintained the harvest time and yield at the same level as those in the nontreated control. Based on the experiments, we concluded that recommended transportation conditions were 6 to 13 °C and that temperature had a more significant impact than light during transportation. The effect of lowering air temperature was validated in a trial 3-d transportation from British Columbia to Arizona (Kubota et al., 2004), in which 95% of trusses exhibited flower abortion or delayed fruit development when air temperature inside the trailer was set at 18 to 19 °C, whereas only 33% showed flower abortion or delayed fruit development at 12 to 13 °C transportation.

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