Abscisic Acid Analogs Reduce Transplant Shock in Tomato Seedlings

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ABSTRACT. Transplant shock results in loss of stand and impairs subsequent performance of seedlings of many horticultural crops. Abscisic acid (ABA) is involved in plant adaptation to a range of environmental stresses including extreme temperatures, wind and soil moisture deficits. Two long-lasting synthetic analogs of ABA, 8′ methylene methyl-ester ABA (PBI 365) and 8′ acetylene methyl-ester ABA (PBI 429) were evaluated for their impact on transplant shock and subsequent agronomic performance of tomato (*Lycopersicon esculentum* Mill.) seedlings. Pre-planting treatment of seedlings with ABA analogs improved their resistance to transplant shock by maintaining higher leaf relative water content, thereby slowing wilting. ABA analog treatments imparted stronger and more persistent effects than racemic ABA. Foliar applications of ABA analogs were less effective than root-dip treatments. PBI 429 was more effective than PBI 365 at preventing transplant shock but it caused dosage-dependent phytotoxic effects that impaired subsequent growth. Under near-ideal cropping conditions, foliar applications of PBI 365 had no effect or a positive effect on crop growth and fruit

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yields. There were no significant responses to varying concentrations of PBI 365 tested, and a single foliar application was as effective as multiple applications. Application of PBI 365 as a root-dip prior to transplanting slowed moisture loss by seedlings, but did not protect the crop against long-term drought stress. The results indicate that treatment of seedlings with an ABA analog prior to transplanting can help prevent the desiccation that is an important part of transplant shock without compromising long-term growth and yield potential of crops. The method and timing of application of the ABA analog needs to be tailored to the degree and duration of stress anticipated following transplanting.

KEYWORDS. *Lycopersicon esculentum*, moisture stress, stand, relative water content, yield

INTRODUCTION

Transplants are commonly used to achieve uniformity of stand, accelerate development and enhance yields of vegetable crops. Maintaining uninterrupted growth after transplanting is a challenge, as the newly planted seedlings have limited and confined root systems and imperfect root-soil contact (Burdett, 1990). Transplanting shock can result in the death of the plant or impair the subsequent performance of the surviving seedlings. Transplanting shock most commonly arises when the transpiration demand exceeds the water uptake capacity of the seedlings' root system (Leskovar, 1998). Drying winds, soil moisture deficits, extremes of temperature and physical injury to the seedlings exacerbates transplanting shock. Transplanting reduces the effective root area and destroys the root hairs that are the predominant region of water absorption (Kramer, 1983), so that seedlings may experience moisture stress, even under relatively favorable field conditions.

Hardening seedlings by exposure to moisture or temperature stress for 1-2 wk prior to transplanting increases the seedlings' tolerance of transplanting shock (Lorenz and Maynard, 1988). Recommended grower practices to reduce transplanting shock include thorough soil preparation and pre-irrigation, choice of planting time to coincide with favorable weather conditions, prompt irrigation after transplanting, mulching and use of crop covers to reduce water loss from the plants and soil. Despite these practices, some degree of transplanting shock is unavoidable, particularly due to unpredictable weather.

The hormone abscisic acid (ABA) is involved in plant acclimation to abiotic stresses such as dehydration, cold and high salt levels (Levitt, 1980). Based on observations with an ABA-deficient tomato mutant, where a normal phenotype was restored through the exogenous application of ABA, Loveys (1991) suggested that ABA treatments might be useful in reducing transplant shock of sensitive plants. Exogenous application of ABA significantly increased stomatal resistance and slowed water use by pepper (*Capsicum annum* L.) seedlings, resulting in less transplanting shock in greenhouse and field experiments (Berkowitz and Rabin, 1988). Exogenously applied ABA has also proven useful in reducing transplanting shock in black spruce (*Picea mariana* Mill.) seedlings (Grossnickle et al., 1996). Foliar applications of ABA decreased transpiration and wilting of pot-grown tomato (*Lycopersicon esculentum* Mill.) and cucumber (*Cucumis sativa* L.) seedlings, but also reduced plant growth (Yamazaki et al., 1995). By reducing stomatal aperture, ABA may exert long-term effects on both plant water status and agronomic performance (Quarrie, 1991). In the longer-term, ABA also changes root growth in a manner that increases water-gathering activity under drought conditions (Jones, 1992).

Agricultural use of ABA is limited by its rapid metabolism in plants, its susceptibility to isomerization to inactive forms by light and by the high cost of its synthesis (Flores and Dorflling, 1990; Abrams et al., 1997). Analogs of ABA have been developed that mimic ABA but are more resistant to degradation and less costly to synthesize (Grossmann and Jung, 1984; Flores and Dorflling, 1990; Schubert et al., 1990; Abrams et al., 1997). Grossnickle et al. (1996) reported improved survival of ABA analog-treated black spruce seedlings under conditions of water stress. Application of 8′ methylene methyl-ester ABA (PBI 365) or 8′ acetylene methyl-ester ABA (PBI 429) reduced plant moisture use but also slowed growth of bedding plants of marigold (*Tagetes patula* L.), petunia (*Petunia* ×*hybrida* Vilm.), tomato and pumpkin (*Cucurbita pepo* L.) in greenhouse studies (Waterer, 2000). When water was withheld from the seedlings, the onset of moisture stress was delayed in transplants treated with the ABA analogs (Waterer, 2000). The effects on drought resistance, plant growth and development were analog and crop specific, and varied with the mode of application and concentration of chemical applied. When the ABA analog-treated seedlings were planted out under relatively favorable field conditions, the effects of the

ABA analog treatments on subsequent plant performance were often negative (Waterer, 2000). However, foliar-application of relatively dilute solutions of the ABA analog PBI 365 produced few negative effects on crop performance under non-stressed conditions and improved plant performance under moisture-stressed conditions (Waterer, 2000).

This study was designed to evaluate the potential for two ABA analogs to protect tomato seedlings against environmental stress encountered following transplanting; to compare the efficacy of the analogs relative to standard ABA; to identify appropriate concentrations and modes of application for the ABA analogs; and to evaluate the effects of the ABA analog treatments on crop yields and quality under both near-optimum production practices or in situations where the crop experienced a significant degree of soil moisture stress for the duration of the growing season.

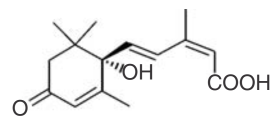
MATERIALS AND METHODS

Transplant Stress Trials: The trials were conducted during the spring of 2000 and 2001. Two days before transplanting into the field, four-week-old, greenhouse-grown tomato (cv. Manitoba) seedlings were treated with racemic methyl-ester of 8′ methylene ABA (PBI 365) or the methyl-ester of 8′ acetylene ABA (PBI 429; Figure 1), synthesized at the Plant Biotechnology Institute, National Research Council of Canada (Abrams et al., 1997; Rose et al., 1997). Racemic ABA (Sigma Co., St. Louis, MO) was employed as the standard ABA comparison.

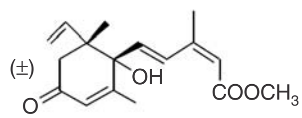
The 2000 trial evaluated the comparative efficacy of 10^{-4} M solutions of the ABA analogs applied as either foliar-spray or root-dip treatments. In the root-dip treatments, 85 cm^3 cell packs containing the tomato seedlings were immersed in the selected ABA analog solution for 2 min. In the foliar-applied treatments, an atomizer was used to apply the ABA treatments to leaf run off. No spreader/sticker was used. On average, 10 mL of solution was required to cover each seedling as a foliar-spray, while 40 mL was required to saturate the media in the root-dip treatments. The chemical was first dissolved in 1% acetone and then diluted with the required volume of water. A 1% acetone solution in water served as the control treatment in both foliar and root-dip applications.

Treatments evaluated in 2001 were modified based on the results from 2000. The ABA analogs and recemic ABA were tested at 10^{-4} and

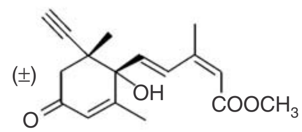
FIGURE 1. Chemical structures of abscisic acid (ABA) and two ABA analogs.



Abscisic acid



8′-methylene ABA methyl ester
PBI-365



8′-acethylene ABA methyl ester
PBI-429

5×10^{-5} M. All treatments were applied as root-dips in 2001, as the foliar application proved relatively ineffective in the 2000 trial.

Two days after treatment with the ABA analogs, the tomato seedlings were hand transplanted into field plots at the University of Saskatchewan, Horticulture Field Research Station, Saskatoon, Canada. The Sutherland series clay soil in the field plots was prepared prior to transplanting by discing and roto-tilling. Recommended amounts of fertilizers (100 and 120 kg·ha^{-1} N and P_2O_5, respectively; Miller, 1988) were incorporated during this tillage. Treatments were arranged in a randomized complete block design with four replicates of each treatment in 2000 and three replicates in 2001. Each replicate consisted of eight plants in 2000 and four plants in 2001. The in-row plant spacing was 50 cm, with 2.5 m between rows. The seedlings were transplanted in the early afternoon and were watered-in with approximately 50 mL of an 11-55-0 fertilizer solution (200 μg·mL^{-1} N). In 2000, no supplemental irrigation was applied at transplanting and no rainfall occurred until 3 d after transplanting. In 2001, irrigation was withheld until the transplants showed obvious moisture stress. In both years, once stress symptoms were observed in most of the treatments, the plots were irrigated to bring the soil moisture content in the root zone to field capacity. Plots were subsequently irrigated weekly to allow evaluation of the impact of the ABA treatments on growth of the transplants under near optimal conditions.

Visual observations on the severity of wilting (% of plants with wilted leaves and drooping tops) were made daily in the early afternoon beginning the day after transplanting. In 2001, the relative water content of the second and third leaves from the top of the plant was also recorded daily at 1400 hrs until stress symptoms were observed in all treatments (Turner, 1981).

The trials were terminated 3-4 wks after transplanting at which point the treatment effects on transplant survival and establishment were distinct. Numbers of surviving plants and shoot fresh weight per plant were measured at that time. These data were subjected to analysis of variance (ANOVA) using an appropriate randomized complete block design (RCBD) model in the GLM program of SAS (SAS Inst., 1987). The data collected over time (wilting % and relative water content) were subjected to analysis of variance (ANOVA) using the repeated measures model described by Gomez and Gomez (1984). All F-tests were carried out at $P = 0.05$. LSD tests ($P = 0.05$) were used for comparisons of treatment means. Pre-planned single degree of freedom contrasts ($P = 0.05$) were also made to evaluate the following main treatment effects: (1) ABA analogs vs. control, (2) analog type, (3) foliar vs. root-dip application, (4) analog type by mode of application, (5) ABA analogs vs. ABA, and (7) ABA vs. control.

Yield Trials: The trials were conducted over the 2000 and 2001 growing seasons at the previously described research site. The site was prepared as previously described and the trials were initiated in the first week of June, after the risk of frost had passed.

In 2000, four-week-old seedlings of tomato (cv. Manitoba) were sprayed as previously described with 10^{-5} M, 5×10^{-5} M or 10^{-4} M concentrations of PBI 365 in 1% acetone 2 d before transplanting into the field. These treatments were chosen as they had shown minimal negative effects on field performance under non-stressed conditions, but had provided some protection from moisture stress in greenhouse and field trials (Waterer, 2000). To test the effect of multiple applications, each concentration of the ABA analog was foliar-applied prior to transplanting, prior to transplanting and again at one week after transplanting, or prior to transplanting and again at one and two weeks after transplanting.

In 2001, a root-dip treatment utilizing PBI 365 at 10^{-4} M applied 2 d before transplanting was evaluated under either fully- or deficit-irrigated conditions. The treatments were arranged in a randomized complete block design (RCBD) in 2000, while the 2001 trial was arranged in a split-plot design with the irrigation regime as the main plot and analog treatments (control versus treated) as the sub-plots. In both trials each treatment was replicated four times and each treatment replicate consisted of eight plants.

In 2000, the tomatoes were transplanted into wavelength selective plastic mulch (IRT 76, Climagro, Saint-Laurent, QB). No mulch was used in 2001, as the objective was to exert moisture stress on the crop. In both years, in-row plant spacing was 50 cm, with 2.5 m between rows. The tomato seedlings were hand-transplanted and watered-in with a fertilizer solution as previously described. Standard management practices designed to minimize crop stress and maximize yields were employed for the duration of the 2000 cropping season. Trickle irrigation lines installed beneath the mulch were used to maintain near-optimal soil water potentials. In the 2001 trial, trickle irrigation lines were used to maintain the soil water potential at 15 cm depth above -30 kPa in the fully-irrigated trial plot. Each time the fully irrigated plot was watered (approx. 2.5 cm), the deficit-irrigation plot received only 50% (1.25 cm) of the water provided to the fully-irrigated regime. Soil water potentials in each replicate of both the fully- and deficit-irrigated plots were measured using tensiometers.

Beginning the day after transplanting, counts were made daily to determine the percentage of transplants that had wilted. Surviving plants were counted two weeks after transplanting. Ripe fruit were harvested weekly beginning in early August. A final harvest was conducted after the first killing frost in late September. At the final harvest, fruit were graded for freedom from defect and according to maturity. Physiologically mature fruit were included in the total marketable yield. Plant fresh weights were also determined following the final harvest.

The data were analyzed using the GLM program of SAS (SAS Institute, 1987). LSD tests ($P \leq 0.05$) were used for comparisons of treatment means. The following pre-planned contrasts of treatment effects were conducted on the 2000 data: (1) ABA analogs vs. control, (2) ABA analog concentration (linear), (3) ABA analog concentration (quadratic), and (4) single vs. multiple foliar application.

RESULTS

Transplant Stress Trials: In both test years, soil moisture levels at the field test site were near field capacity at the time of transplanting. Immediately following transplanting, temperatures were moderate (average 23/16°C day/night) with no rainfall within the first 3 days after transplanting.

2000 Trial

Symptoms of moisture stress and transplanting shock were observed in the control treatment within a day of transplanting and persisted and/or worsened through to the end of the four-week trial. The interaction between time after transplanting and the effect of the ABA treatments on wilting of transplants was significant, indicating a change in treatment effects over time (Table 1). When ABA analogs were applied as a foliar treatment, the seedlings showed a progressive increase in wilting over the evaluation period, whereas negligible wilting occurred with the root-dip application (Table 1). PBI 365 was consistently less effective at preventing wilting than PBI 429 (Table 1).

Of plants treated with the ABA analogs, 82% survived through to the conclusion of the trial compared to 42% survival in the control (Table 1). All of the root-dip treated plants survived to the termination of the trial compared to 64% of the foliar-applied treatments. Regardless of the mode of application, 98% of the PBI 429 treated plants survived compared to 66% of PBI 365 (Table 1). When applied as a root-dip, the two analogs were equally effective at preventing transplant wilting and death, but PBI 429 was more effective than PBI 365 when applied as a foliar spray.

Growth in the 4 wks following transplanting was minimal in the control treatment (Table 1). The mode of application and the interaction between analog type and mode of application influenced shoot fresh weights of the ABA-treated seedlings at 4 wks after transplanting. Root-applied PBI 365 produced the highest mean shoot fresh weights while the other treatments were similar to the control (Table 1). The foliar-applied PBI 365 was ineffective at preventing transplanting stress and growth after transplanting was limited in this treatment. Although root-applied PBI 429 prevented wilting, it also retarded subsequent growth of the transplants.

TABLE 1. Analysis of variance, single degree of freedom contrast mean squares and treatment means for seedling wilting at 1 and 3 d after transplanting and survival and shoot fresh weights 4 wks after transplanting for tomato seedlings treated prior to transplanting with ABA analogs via foliar or root-dip application (2000 trial).

	Mean square			
Source of variation	Plants wilted		Seedling survival	Shoot weight
ABA treatment (A)	1.42**		25.84**	202.3**
Time (T)	0.0791*		--	--
A × T	0.00586**		--	--
Contrasts				
Analog vs. control	1.25**		28.50**	194.64*
Analog type	2.96**		27.56**	84.08 ns
Foliar vs. root	0.86**		33.06**	89.58 ns
Analog × application type	0.95**		27.56**	642.11**
Treatment means	Plants wilted (%)		Seedling survival (%)	Shoot fresh wt. (g)
	Day 1	Day 3		
PBI 365 10^{-4} M[F]	98.5	100.0	31.2	8.8
PBI 365 10^{-4} M[R]	0.0	9.5	100.0	26.2
PBI 429 10^{-4} M[F]	59.5	80.0	96.9	16.8
PBI 429 10^{-4} M[R]	0.0	5.3	100.0	8.9
Control[F]	100.0	100.0	37.5	9.3
Control[R]	100.0	100.0	45.8	9.0
$LSD_{(0.05)}$	7.1		11.0	8.8

ns,*,** = Non-significant or significant at $P = 0.05$ or 0.01, respectively.
F = Foliar spray, R = Root-dip.

2001 Trial

The relative leaf water content averaged over the 3 d recording period were consistently higher in the ABA analog-treated plants compared to the controls and plants treated with racemic ABA (Table 2). Plants treated with 10^{-4} M solutions of the analogs had higher leaf relative water contents than those receiving 5×10^{-5} M. Relative water content was not influenced by analog type (Table 2).

Untreated control plants wilted within a day of transplanting, as did most plants treated with racemic ABA as a root dip (data not shown). By

TABLE 2. Analysis of variance, single degree of freedom contrast mean squares and treatment means for leaf relative water content and wilting percentage averaged over the 3 d after transplanting and shoot fresh weights at 4 wks after transplanting for tomato seedlings treated prior to transplanting with ABA or ABA analogs (PBI 365 or PBI 429) as root-dips (2001 trial).

	Mean square		
Source of variation	Relative water content	Wilting	Shoot fresh weight
ABA treatment (A)	0.0947^{**}	0.738^{**}	341.89^{**}
Time (T)	0.0313^{**}	0.335^{**}	–
A × T	0.000396^{ns}	0.0223^{ns}	–
Contrasts			
Analog vs. control	0.4033^{**}	2.93^{**}	61.46^{ns}
Analog vs. ABA	0.243^{**}	1.92^{**}	36.86^{ns}
ABA vs. control	0.0535^{**}	0.340^{**}	8.20^{ns}
Analog type	0.00134^{ns}	0.127^{**}	670.05^{**}
Analog conc.–linear	0.0470^{**}	0.210^{**}	1185.44^{**}

Treatments	Relative water content (%)	Wilting (%)	Shoot fresh wt. (g)
PBI 429 10^{-4} M	77.5	0	11.0
PBI 429 5×10^{-5} M	71.0	12.5	35.8
PBI 365 10^{-4}	79.4	8.3	30.9
PBI 365 5×10^{-5} M	71.5	33.3	45.9
ABA 10^{-4} M	60.0	50.0	25.1
ABA 5×10^{-5} M	61.3	75.0	30.6
Control	51.2	91.6	25.6
$LSD_{(0.05)}$	7.0	14.8	12.0

^{ns,*,**} = Non-significant or significant at P = 0.05 or 0.01, respectively.

contrast, plants treated with the ABA analogs did not wilt until 3 d after transplanting. Averaged over the 3 d evaluation period, PBI 429 treatments were more effective at slowing wilting than PBI 365 treatments. Plants receiving the 10^{-4} M concentration of the ABA analogs exhibited less wilting than the 5×10^{-5} M treatments. Wilting percentages obtained using 5×10^{-5} M of the two ABA analogs were statistically equivalent to those obtained when racemic ABA was applied at a five-fold higher concentration (Table 2).

All transplants survived in the 2001 trial, as the plots were thoroughly irrigated within 3 d of transplanting. When seedlings were harvested at 3 wks after transplanting, the PBI 365 treatments produced higher mean shoot fresh weights than the PBI 429 treatments (Table 2). The 10^{-4} M concentrations of ABA analogs reduced growth relative to the 5×10^{-5} M concentration. Plants treated with PBI 365 at 5×10^{-5} M produced greater shoot fresh weights than the controls.

Yield Trials: Unless otherwise specified, growing conditions were generally favorable in both growing seasons and no biotic stress factors were observed.

2000 Trial

Air temperatures exceeded 30°C on the day of transplanting in 2000 and within a few hours of transplanting all the seedlings wilted, irrespective of the ABA treatment applied. Subsequent weather conditions were more favorable and no further visual symptoms of transplanting shock were observed. All the seedlings survived in all treatments. On average, at the final harvest, shoot weights of the ABA analog treated plants were greater than the control (Table 3). Marketable fruit yield was also marginally higher ($P > F = 0.07$) for ABA analog-treated plants than for the controls. The number of times the ABA analogs were applied (single or multiple) and the concentration of ABA analog applied had no effect on any of the parameters recorded (Table 3).

2001 Trial

Total rainfall during the 2001 cropping season was 8.8 cm, with an additional 13.7 cm of irrigation applied in the deficit-irrigated regime and 28.7 cm in the fully-irrigated regime. Soil water potentials in the deficit-irrigated plots ranged from 0 to −60 kPa over the course of the growing season (avg −37 kPa) (Figure 2). Due to frequent light rain and the high moisture retention capacity of the clay soil at the test site, soil water potentials in the deficit-irrigated plots remained above the stress threshold of −30 kPa for the first two weeks after transplanting. In the fully-irrigated plots soil water potentials ranged from 0 to −30 kPa (avg −14 kPa).

Untreated control plants wilted within a day of transplanting under both irrigation regimes; while the ABA analog-treated seedlings did not wilt (data not presented). By the third day after transplanting, the untreated control plants in both irrigation regimes had recovered from the

TABLE 3. Treatment means and P-value probabilities for single degree of freedom contrasts for growth and yield of tomato treated with varying concentrations of PBI 365 as single or multiple foliar applications–2000 trial.

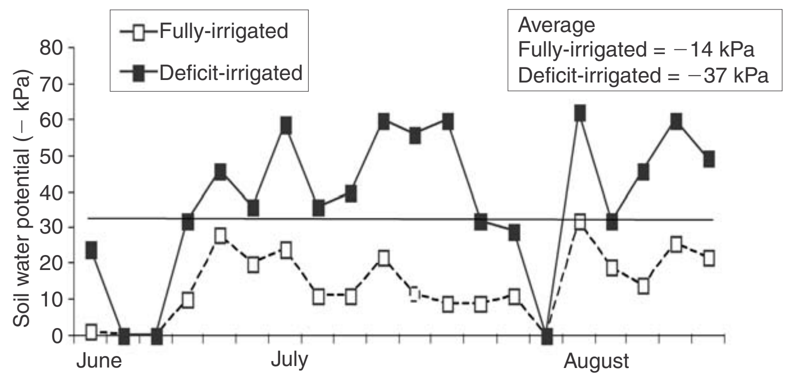
Source	Shoot fresh weight (kg/plant)	Marketable fruit yield (kg/plant)
ABA		
None	2.1	5.5
PBI 365	2.5	6.3
P-value	< 0.01	NS (0.07)
ABA concentration		
10^{-5} M	2.3	6.0
5×10^{-5} M	2.1	6.0
10^{-4} M	2.4	6.6
P-value		
Linear	NS	NS
Quad	NS	NS
ABA applications		
One[x]	2.4	6.6
Two[y]	2.2	6.0
Three[z]	2.3	6.0
P-value		
Linear	NS	NS
Quad	NS	NS

[x, y, z] = Applied prior to transplanting, applied prior to transplanting and again one week after transplanting, applied prior to transplanting and again at one and two weeks after transplanting, respectively.
NS = $P > 0.05$.

transplant shock and no wilting was observed in any treatment for the duration of the trial. Stand counts were above 90% in all treatments and were not affected by either the irrigation or ABA analog treatment variables (data not shown).

Averaged over the ABA treatments, the full-irrigation regime produced larger shoots (1.1 versus 0.9 kg/plant) and greater fruit yields (6.5 versus 4.7 kg/plant) than the deficit-irrigation regime. Treatment with the ABA analog had no significant effect on any growth or yield parameter, irrespective of the irrigation regime.

FIGURE 2. Soil water potentials over the 2001 growing season (June-August). Horizontal line (−30 kPa) represents the soil moisture deficit threshold used in this trial.



DISCUSSION

Treatment of tomato seedlings with ABA analogs prior to transplanting slowed moisture loss by the seedlings, mitigating one of the primary causes of transplant shock. Application of ABA and ABA analogs has been shown to reduce stomatal aperture and transpiration (McKee, 1978; Jones, 1992; Sharma 2002), leading to a corresponding slowing of plant moisture use and improved transplant survival (Berkowitz and Rabin, 1988; Grossnickel et al., 1996).

The ABA analogs were superior to racemic ABA at preventing transplant shock of tomato seedlings. The greater biological activity of the ABA analogs is likely due to the slower metabolism of the analogs within the target plant (Abrams et al., 1997; Cutler et al., 2000). The efficacy of the ABA analogs varied with concentration, mode of application and analog type. Efficacy increased with the concentration of ABA analog applied, particularly when the ABA solutions were applied as a root drench. PBI 429 was more effective than PBI 365, particularly when used as a foliar treatment. PBI 429 appears to be more physiologically active, with greater resistance to oxidative breakdown within the plant than PBI 365 (Abrams, unpublished data). The reason root-applied treatments of both analogs were more effective than foliar applications could be attributed to the greater quantities of chemical applied and retained in the root-dip treatments versus foliar applications. Arteca and Tsai (1987) note that the leaf cuticle may hinder absorption of foliar-applied ABA. No corresponding barrier to absorption exists in the roots.

When protecting seedlings against transplant stress, the ideal treatment would provide the required degree and duration of protection without compromising long-term growth. When tomato seedlings were exposed to adverse conditions for a brief period at the time of transplanting, but subsequently maintained under near-ideal growing conditions and crop management practices for the remainder of the growing season, foliar application of an ABA analog prior to transplanting nonetheless improved vegetative growth and to a lesser extent fruit yields. Greater treatment effects might be expected in more stress-sensitive crops and/or when less favorable conditions prevail following transplanting (Sharma, 2002). Post-planting application of ABA may also prove beneficial if prevailing conditions do not favor crop establishment. The fact that none of the foliar-applied ABA analog treatments tested had any negative effects on growth or yields suggests that these treatments could be employed as insurance against mild or transient adverse conditions without compromising crop performance should growing conditions remain favorable.

The greater strength and durability of treatment effects provided by the root-dip method of treatment might be desirable in situations where plants are exposed to more severe or extended periods of stress following transplanting. This theory was tested with the application of a relatively high concentration of PBI 365 (10^{-4} M) as a root-dip to tomato seedlings prior to planting out into field plots maintained under deficit-irrigation regimes for the remainder of the growing season. Although this ABA analog treatment protected the seedlings against desiccation immediately following transplanting, it did not protect against the growth suppression and yield loss caused by longer-term drought stress. Although an ABA-induced reduction in transpirational moisture loss may help protect seedlings against desiccation, any reduction in stomatal aperture would also reduce CO_2 uptake (Arteca and Tsai, 1987; Loveys, 1991; Salisbury and Ross, 1992). Consequently, treatment with ABA analogs may slow growth and reduce yields unless benefits associated with increased stress resistance exceed the cost associated with the ABA-induced reduction in photosynthetic capacity. This situation would occur in crops exposed to severe but short-term stress at transplanting, a situation which often occurs during commercial production. In this trial, moisture stress following transplanting was relatively mild due to the combination of cool growing conditions, limited crop water use and the abundant moisture reserves available in the clay soil at the test site. No supplemental irrigation was required for nearly 4 weeks after planting, by which time the seedlings in all treatments were well established. Stronger and more durable ABA analog treatments may be more appropriate to situations where moisture reserves available to the seedling are more rapidly or severely depleted.

Transplant shock was ameliorated by pre-planting application of ABA analogs as either foliar treatments or root-dips. The ABA analog treatments enhanced the water status of transplanted seedlings and delayed wilting after transplanting in a dosage-dependent manner. Benefits of the ABA treatments were observed even under relatively favorable conditions, suggesting even greater potential benefits if heat or moisture stress are anticipated following transplanting. By selecting the appropriate analog type, concentration, method and timing of delivery, the strength and duration of efficacy of the ABA analog treatments may be tailored to match the field situation. The efficacy and cost efficiency of the ABA analogs need to be evaluated relative to other methods for enhancing resistance to transplanting stress.

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