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HORTSCIENCE 36(6):1127–1130. 2001.

Storage and Handling Characteristics of Trinexapac-ethyl Treated Kentucky Bluegrass Sod

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Additional index words. Poa pratensis, plant growth regulators, stress tolerance

Abstract. **Internal heating during sod storage can lead to plant deterioration and is a limiting factor in sod transportation. Storage practices such as the use of refrigeration and vacuum packaging have increased storage time; however, these are usually not practical or economical. Experiments were conducted to develop a feasible growth regulator management technique, using trinexapac-ethyl, to increase the storage life of Kentucky bluegrass (*Poa pratensis* L.) sod. Experimental setup for all experiments was a completely randomized design with a 2 (trinexapac-ethyl vs. control) × 3 (storage times) factorial treatment arrangement with 3 replications. Trinexapac-ethyl was applied at 0.23 kg·ha^{-1} to Kentucky bluegrass 2 weeks prior to harvesting. Results showed that sod treated with trinexapac-ethyl was as much as 10 °C cooler than the controls in the center of the sod stacks after 48 hours of storage. The reduced sod temperatures led to a 30% greater tensile strength and 17% better quality ratings in treated sod after 24 hours of storage. A preharvest application of trinexapac-ethyl appears to increase storage times of Kentucky bluegrass sod, which may improve sod market quality. Chemical name used: [4(cyclopropyl-α-hydroxy-methylene)-3,5-dioxocyclohexanecarboxylic acid ethyl ester] (trinexapac-ethyl).**

Kentucky bluegrass is the predominant cool-season turfgrass utilized in North American sod production (Christians, 1998). Internal heating of sod when it is stored can cause plant deterioration, limiting the distance sod can be transported. Damage to sod from heat can decrease market quality. Sod quality consists of both sod tensile strength and sod transplant rooting strength. Sod tensile strength is the ability of sod to resist tearing during handling and installation (Christians, 1998). Plastic netting can be applied to sod in the field at the time of seeding or at harvest to increase sod strength, but it is expensive and is avoided whenever possible. Sod transplant rooting strength is the ability of sod to quickly recover and establish a vigorous root system in order to become functional, that is, to withstand wear or provide acceptable erosion control. Other sod quality characteristics necessary for marketable sod include uniformity, high shoot density, acceptable color, absence of weeds, disease, and pests, and minimal thatch (Beard and Rieke, 1969).

Sod is traditionally cut into sections and stacked on pallets or placed in rolls after harvest for storage and shipment (Christians, 1998). Heat accumulation within sod stacked on pallets or within rolls has a negative influence on sod quality. Heat accumulation can cause a rapid decline in quality and can eventually lead to plant death (King, 1970). Common bermudagrass [*Cynodon dactylon* (L.) Pers.] sod stored on pallets heated to 12 °C above ambient temperature after 5 days of storage (Maw et al., 1998). King et al. (1982b) identified an increase in CO_2 and decreased O_2 levels in sod accumulating heat, indicating active plant respiration during the early stages of sod storage. Low vapor pressure deficits can also lead to higher sod temperatures due to less latent heat transfer.

Darrah and Powell (1977) reported creeping red fescue (*Festuca rubra* L.) sod had a higher rate of heating in sod stacks when the turf was mowed at 7.6 cm compared to 2.5 cm. Kentucky bluegrass sod mowed at 5 cm had twice as much damage as sod mowed at 2 cm after being stored for 72 h. Sod fertilized with 40.5 kg·ha^{-1} nitrogen resulted in 3.5 °C higher temperatures within sod stacks after 72 h of storage than controls (Darrah and Powell, 1977). King et al. (1982a) measured more than four times the amount of leaf injury to Kentucky bluegrass sod fertilized with 240 kg·ha^{-1} nitrogen compared to no application of nitrogen after 48 h of storage. The presence of clipping residues also resulted in an increase of 3.6 °C within sod stacks 48 h after harvest compared to sod with no clippings (Darrah and Powell, 1977). Temperature of sod harvested early in the morning was 5.8 °C lower than that of sod harvested later in the day (Darrah and Powell, 1977). Sod storage temperatures can be reduced by refrigeration or vacuum packaging. These storage techniques are expensive and may not be feasible for many sod growers.

Chemicals may be used to reduce sod temperatures when stored, resulting in improved turf quality. The biostimulant benzyladenine and the fungicide propiconazole have been found to increase Kentucky bluegrass sod tensile strength as much as 23% (Goatley and Schmidt, 1991). However, these chemicals have not been readily adopted for use in commercial turf production. Plant growth regulators (PGRs) are widely used for turf management. These PGRs are either natural or synthetic compounds that are applied directly to target plants for altering metabolic processes or structures to improve quality, increase yields, or facilitate harvesting (Nickell, 1982). Turfgrass PGR development has targeted the reduction of clipping yields.

The PGRs amidochlor [*N*-({acetylamino} methyl)-2-chloro-*N*-(2,6-diethylphenyl) acetamide], flurprimidol [α-(1-methylethyl)-α-{4-(trifluoromethoxy)phenyl}-5-pyrimidinemethanol], and mefluidide [*N*-(2,4-dimethyl-5-{[trifouromethyl)sulfonyl]amino} phenyl)acetamide] have been shown to reduce net photosynthesis of cool-season grasses (Gaussoin et al., 1997; Spokas and Cooper, 1991). This may lead to generally lower plant metabolism. Qian et al. (1998), however, reported increased photosynthesis of trinexapac-ethyl treated zoysiagrass [*Zoysia matrella* (L.) Merr.] in the shade. Heckman (2000) documented a decrease in respiration of isolated wheat mitochondria in the presence of trinexapac-ethyl. Plant respiration is one of the major causes of sod heating.

The objective of this study was to determine the effects of preharvest application of trinexapac-ethyl on Kentucky bluegrass sod tensile strength, sod storage temperatures, and turf color and quality after transplanting.

Materials and Methods

A Kentucky bluegrass sod blend of 'America', 'Apex', 'Eclipse', and 'Midnight' cultivars grown at Todd Valley Farms near Mead, Nebr., on a Tomek silty clay loam (fine, smectitic, mesic Typic Argiudoll) was used for two separate experiments. Twenty-six-month-old sod was treated with trinexapac-ethyl at 0.23 kg·ha^{-1} with a sprayer at 0.21 MPa to achieve a delivering rate of 561 L·ha^{-1} on 24 May 1998. Sod was harvested with a mechanical sod cutter into 51 × 102 cm sections 1.9 cm thick, on 7 June 1998. After harvesting, the sod was immediately stacked on pallets to make up forty 102 × 102 cm layers, with each layer consisting of two sod sections. The direction of the sod sections on pallets were varied after every five layers to increase the stability of the sod stacks. Nine sod stacks contained Kentucky bluegrass treated with trinexapac-ethyl and nine sod stacks were un-

Received for publication 25 Aug. 2000. Accepted for publication 6 Feb. 2001. Univ. of Nebraska–Lincoln, Agricultural Research Division journal series number 12876. We thank L.A. Wit for preparation of the sod storage site and technical support in the field. 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.

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treated controls. Thermocouples were placed in six treated and six control sod stacks. Thermocouples were arranged on a vertical shaft aligned through the center of each stack and placed at the depths of 31.5 and 91.5 cm from the bottom of the stack. A horizontal shaft was centered on layer 20 and thermocouples were set at 2.5, 10.2, 20.3, and 30.5 cm from the center of the sod stacks. The thermocouples were connected to a CR7 data logger (Campbell Scientific, Logan, Utah), to record hourly temperatures. Sod stacks were stored in a completely randomized design at the John Seaton Anderson Research Facility near Mead, Nebr., and were exposed to ambient weather conditions. Air temperature and precipitation were recorded hourly during sod storage.

Sod storage times began when sod arrived at the research site ≈2 h after harvest. At 24, 48, and 72 h of storage, sod from the center three layers were planted in a completely randomized design forming 204 × 153-cm plots. At these same intervals, sod tensile strength (STS) was determined from layers 22 and 23 from the bottom of the stacks. A sod stretcher, similar to the one used by Sharpe et al. (1989) was used to determine tensile strength. Sections of sod ≈34 × 51 cm were placed on a platform grate and strapped securely with a nylon band. Half of the sod section was on a stationary grate, while the other half was on a mobile grate. A sash chain was connected to a winch and the mobile grate. An "S" beam load cell attached to the chain measured peak resistance (Giese et al., 1997). Sod tensile strength was recorded as the resistance of sod to longitudinal stress measured by the minimum amount of longitudinal stress required to separate the sod. Three subsamples of STS were measured from sod on the pallets at 24, 48, and 72 h of storage.

A second experiment was conducted in 1999. Sod that was 20 months old was treated with 0.23 kg·ha^{-1} trinexapac-ethyl on 25 May and harvested on 8 June as described for the 1998 experiment. Thermocouple arrangement was the same as earlier and temperatures were recorded every 30 min. At 12, 24, and 48 h after harvest, sod was planted and STS was measured. Four subsamples of STS were taken from each sod stack in this experiment.

Visual color and quality ratings were measured at 2, 4, and 6 weeks after the last sod sections were planted in 1999. Color and quality ratings were taken using a 1 to 9 scale on the turf that survived the temperatures in the sod stacks. A color or quality rating of <6 was unacceptable, 6 was acceptable for home lawn use, and 9 was the best color and quality.

Air temperatures and relative humidity were measured hourly for the two experiments. Vapor pressure deficits were calculated using the equations derived by Rosenberg et al. (1983a) and compared for the two experiments using Student's paired *t* test.

Experimental design for both experiments was a completely randomized design with a 2 (trinexapac-ethyl vs. control) × 3 (storage times) factorial treatment arrangement with three replications. Sod storage temperature data were modeled using multiple linear regression and graphed using PlotIt software (Scientific Programming Enterprises, Haslett, Mich.). Tensile strength data were compared using Student's paired *t* test on the subsamples, while color and quality ratings were analyzed using analysis of variance within the Statistical Analysis System (SAS, 1988). Experiments were analyzed separately for different storage time intervals and sod age.

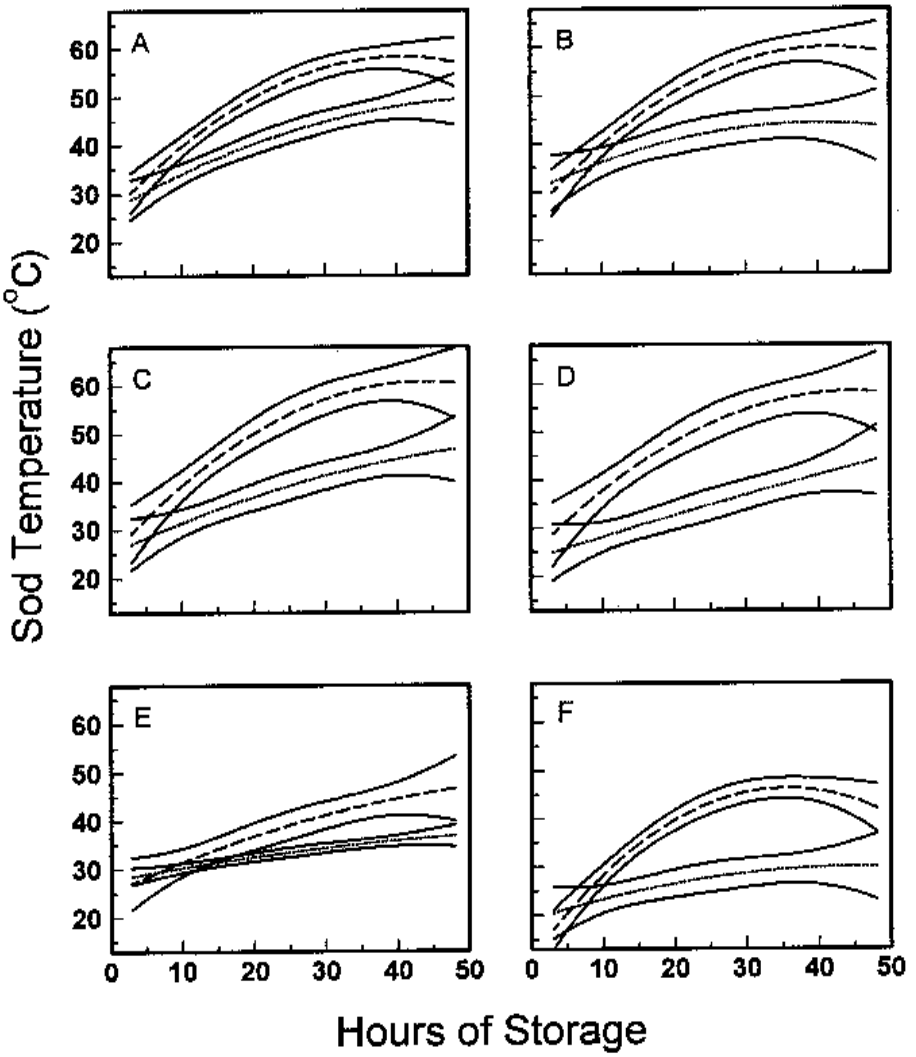

Fig. 1. Sod temperatures in June 1998 of Kentucky bluegrass treated with 0.23 kg·ha^{-1} trinexapac-ethyl (**…**) and controls (---) from 3 to 48 h of storage; 99% confidence intervals (—) are around each regression line. (**A**) Measurements taken 2.5 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 26.37 + 0.8511x - 0.007682x^2$ ($R^2 = 0.330$) control (---) $y = 25.68 + 1.614x - 0.01989x^2$ ($R^2 = 0.498$). (**B**) Measurements taken 10.2 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 29.88 + 0.7196x - 0.008987x^2$ ($R^2 = 0.298$) control (---) $y = 25.1 + 1.681x - 0.02021x^2$ ($R^2 = 0.444$). (**C**) Measurements taken 20.3 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 25.15 + 0.6832x - 0.004875x^2$ ($R^2 = 0.451$) control (---) $y = 24.62 + 1.654x - 0.0189x^2$ ($R^2 = 0.609$). (**D**) Measurements taken 30.5 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 23.55 + 0.4685x - 0.0008735x^2$ ($R^2 = 0.403$) control (---) $y = 24.36 + 1.511x - 0.01679x^2$ ($R^2 = 0.519$). (**E**) Measurements taken 30.5 cm vertically from the center of the bottom of the sod stacks. Fitted lines: trinexapac-ethyl (---) $y = 27.78 + 0.271x - 0.0017x^2$ ($R^2 = 0.290$) control (…) $y = 22.77 + 0.7113x - 0.006072x^2$ ($R^2 = 0.443$). (**F**) Measurements taken 91.5 cm vertically from the center of the bottom of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 19.2 + 0.4687x - 0.005083x^2$ ($R^2 = 0.247$) control (---) $y = 11.47 + 1.963x - 0.02761x^2$ ($R^2 = 0.508$).

Results and Discussion

Sod treated with 0.23 kg·ha^{-1} of trinexapac-ethyl prior to harvest accumulated less heat than controls in storage in experiments conducted in June 1998 and 1999 (Figs. 1 and 2). Sod temperatures were higher in the center of the sod stacks than closer to the edge. Sod segments closest to the surfaces were more influenced by ambient air temperature, similar to dependence of soil within 20 cm from the surface on ambient air temperature (Rosenberg et al., 1983b). Temperature differences between trinexapac-ethyl and untreated sod developed more quickly in 1998 than 1999, possibly a result of equipment failure that resulted in a 5-h delay in 1998. King (1970) estimated that exposure to 40 °C caused a

significant amount of plant death for 'Merion' Kentucky bluegrass. Sod in the center of the sod stacks could have been stored >10 h longer without reaching lethal temperatures in 1998, if we assume that the cultivar blend of Kentucky bluegrass used in these experiments has a lethal temperature similar to 'Merion' Kentucky bluegrass. Temperatures within sod stacks were as much as 15 °C lower in June 1999 than in June 1998 after 48 h of storage (Figs. 1 and 2). No precipitation occurred during sod storage either year, but mean air temperatures in 1998 were 13 °C cooler and closer to optimal (Fig. 3). This would not have put the turf under as much stress. Also, a greater mean vapor pressure deficit in 1999 of 0.43 KPa ($P < 0.001$) may have resulted in more latent heat transfer from the sod stacks. Both of these factors could account for higher sod temperatures in 1998.

The effect of trinexapac-ethyl on sod storage temperatures may result from a decrease in plant respiration. It has been shown that trinexpac-ethyl decreases respiration of isolated wheat mitochondria (Heckman, 2000). Trinexapac-ethyl contains two double-bonded oxygens on a hexane ring. This is a similar structure to ubiquinone, which is a major component of the mitochondrial electron transport chain. Heckman (2000) proposed that this similarity in structure may allow trinexapac-ethyl to accept electrons in a manner similar to ubiquinone. However, the difference in the other functional groups may not allow trinexapac-ethyl to pass electrons from the ubiquinone pool. Consequently, trinexapac-ethyl could fit into quinone or quinol binding sites and competitively inhibit these activities, resulting in lower respiration. Other chemicals have been shown to inhibit respiration. The pesticides 2,4-*D* [(2,4-dichlorophenoxy) acetic acid] and trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine] have been shown to directly inhibit mitochondrial respiration by disrupting electron transport (Moreland and Huber, 1979; Moreland et al., 1972; Switzer, 1957). If trinexapac-ethyl decreases the respiration of Kentucky bluegrass we would also expect lower temperatures inside the stacks of sod that were treated with trinexapac-ethyl.

The influence of microorganisms on sod heating can not be ignored. Microbial respiration is a major cause of sod heating (Christians, 1998). The amount of heating due to microbial respirations compared to plant respiration in a sod system is unknown. From our data, we can not be sure if the specific site of action is on the plant, microbes, or both. Further research in this area needs to be conducted to fully understand this phenomenon.

Secondary effects on sod heating of overall sod quality were noted. Sod tensile strength was shown to be significantly greater after 24 h of storage in June 1998 for sod treated with trinexapac-ethyl compared to the control (Table 1). It is highly unlikely that one application of trinexapac-ethyl increased the density of the roots in the sod, which would increase the tensile strength. It is much more probable that the higher temperature inside the sod stacks during June 1998 for the controls had a serious negative effect on the tensile strength. There was a negative relationship between sod tensile strength and the amount of time the sod was left in the sod stacks. This probably is a result of the heat accumulation within the sod stacks. Therefore, trinexapac-ethyl may have maintained the sod tensile strength by decreasing the temperatures within the sod stacks.

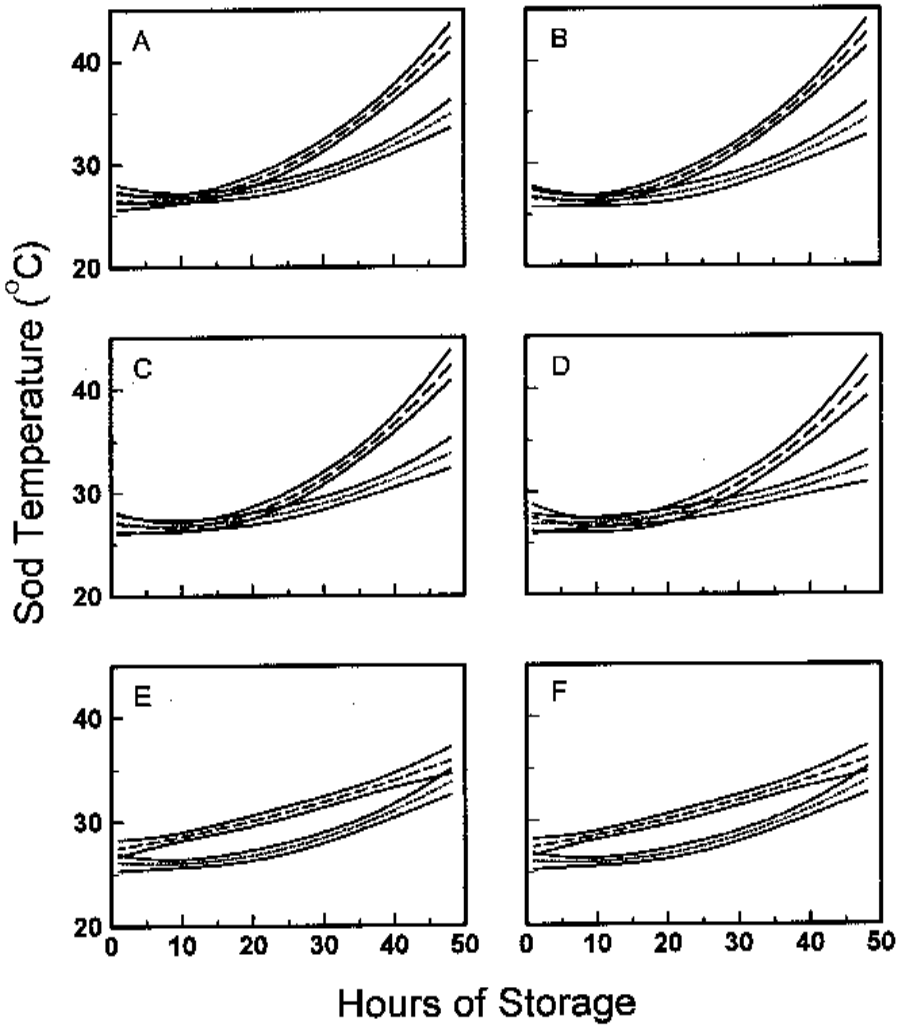

Fig. 2. Sod temperatures in June 1999 of Kentucky bluegrass treated with 0.23 kg·ha^{-1} trinexapac-ethyl (…) and controls (---) from 1 to 48 h of storage; 99% confidence intervals (—) are around each regression line. (**A**) Measurements taken 2.5 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 27.37 - 0.1155x + 0.00566x^2$ ($R^2 = 0.560$) control (---) $y = 26.65 - 0.08611x + 0.008535x^2$ ($R^2 = 0.852$). (**B**) Measurements taken 10.2 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 26.97 - 0.1202x + 0.005652x^2$ ($R^2 = 0.486$) control (---) $y = 26.78 - 0.1207x + 0.009326x^2$ ($R^2 = 0.861$). (**C**) Measurements taken 20.3 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 27.08 - 0.0702x + 0.004399x^2$ ($R^2 = 0.475$) control (---) $y = 27.4 - 0.1671x + 0.009934x^2$ ($R^2 = 0.820$). (**D**) Measurements taken 30.5 cm horizontally from the center of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 26.96 - 0.02514x + 0.0029x^2$ ($R^2 = 0.356$) control (---) $y = 27.78 - 2.089x + 0.01009x^2$ ($R^2 = 0.697$). (**E**) Measurements taken 30.5 cm vertically from the center of the bottom of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 26.24 - 0.07034x + 0.0047646x^2$ ($R^2 = 0.632$) control (---) $y = 27.42 + 0.1013x + 0.001595x^2$ ($R^2 = 0.654$). (**F**) Measurements taken 91.5 cm vertically from the center of the bottom of the sod stacks. Fitted lines: trinexapac-ethyl (…) $y = 25.08 - 0.09508x + 0.003461x^2$ ($R^2 = 0.493$) control (---) $y = 25.39 - 0.08866x + 0.005763x^2$ ($R^2 = 0.687$).

Visual color and quality ratings were taken after transplanting the sod in 1999. A significant trinexapac-ethyl treatment × storage time × weeks after replanting interaction occurred for both color and quality. Trinexapac-ethyl treatment × storage time interaction was not statistically significant, so all data were pooled over trinexapac-ethyl treatment and storage time, and analyzed separately for weeks after replanting. Color ratings at 2 weeks after transplanting showed a significant decrease in visual color for sod stored for 48 h compared to sod stored for 12 and 24 h (data not shown). This was expected since turf stored for longer periods of time was exposed to more heat. Color was also enhanced by trinexapac-ethyl. The color of treated sod was superior to the controls 4 weeks after transplanting (Table 2).

Trinexapac-ethyl treatment and storage time had similar influences on turf quality. Sod that had been transplanted after storage

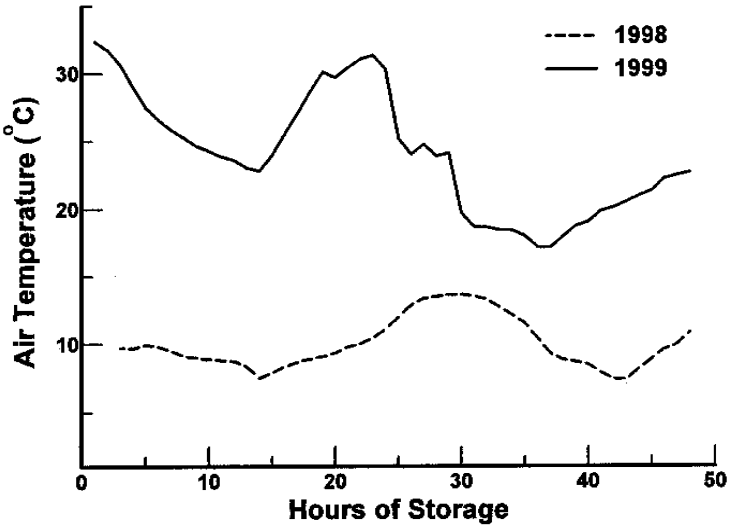

Fig. 3. Air temperatures in June 1998 and June 1999 during sod storage near Mead, Nebr.

Table 1. Effects of 0.23 kg·ha^{-1} trinexapac-ethyl on Kentucky bluegrass sod tensile strength after storage on a pallet near Mead, Nebr.

	June 1998			June 1999		
	Hours after harvest					
Treatment	24	48	72	12	24	48
	kg					
Trinexapac-ethyl	65.6[z]	30.4	5.6	25.3	20.1	10.4
Control	50.2	20.0	11.7	22.5	17.1	8.7
$LSD_{0.05}$	13.1	NS	NS	NS	NS	NS

[z]Data are expressed as mean resistance of sod to longitudinal stress measured by the minimum amount of longitudinal stress required to separate the sod.
[NS]Nonsignificant.

Table 2. Influence of 0.23 kg·ha^{-1} trinexapac-ethyl on the color and quality of sod after being stored on a pallet in June 1999 near Mead, Nebr.

	Color[z]			Quality[y]		
	Weeks after transplanting					
Treatment	2	4	6	2	4	6
Trinexapac-ethyl	6.9	7.4	6.9	6.6	7.2	6.8
Control	6.1	6.3	6.9	5.6	6.4	6.6
$LSD_{0.05}$	NS	0.9	NS	0.9	NS	NS

[z]Sod color ratings were based on a 1 to 9 scale, where <6 unacceptable; 6 was acceptable for home lawn use; 9 was best.
[y]Sod quality ratings were based on a 1 to 9 scale, where <6 unacceptable; 6 was acceptable for home lawn use; 9 was best.
[NS]Nonsignificant.

for 12 and 24 h had better quality ratings than sod stored for 48 h (data not shown). Trinexapac-ethyl treated sod 2 weeks after transplanting had higher quality ratings than controls (Table 2). Sod grew rapidly due to high amounts of rainfall and relatively cool temperatures for the first 4 weeks after transplanting. This may have led to no detectable color and quality differences 6 weeks after transplanting.

A preharvest application of trinexapac-ethyl appears to increase storage life of Kentucky bluegrass sod, which may improve sod market quality. Application of 0.23 kg·ha^{-1} of trinexpac-ethyl in June, 10 or 14 d prior to the harvest of sod, effectively reduced temperatures within sod stacks, sustained tensile strength longer, and improved posttransplant quality. Previous trinexapac-ethyl research has focused on the reduction of clipping yield and little is documented on alternative turfgrass effects. Therefore, the physiological basis for this phenomenon is not certain. Additional research needs to be completed to further understand the influence of trinexpac-ethyl on storage temperatures and sod quality.

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