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Foliar applications of alcohols failed to enhance growth and yield of C_3 crops

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Abstract

Nonomura and Benson, Proc. Natl. Acad. Sci., 89, 1992, 9794–9798, applied methanol to foliage of numerous C_3 crops in the warm and arid growing conditions of Arizona, and established marked increases in biomass production and water-use efficiency. The main objectives of our experiments were to: (1) evaluate whether methanol and ethanol enhance growth of C_3 crops; (2) determine the most efficacious alcohol concentration for foliar application; (3) establish the optimal time and number of applications; and (4) assess whether methanol, which is toxic, could be substituted with ethanol. Experiments were done in the field and greenhouse conducted at Viikki Experimental Farm, University of Helsinki, Finland (60°13′N) in 1994 and 1995. Crops included spring cereals (barley, wheat, and oat), pea and summer turnip rape. Leaf chlorophyll content, fluorescence, phytomass, grain yield, hectoliter weight, thousand kernel weight, and harvest index were measured. The results from these experiments indicated that, in general, alcohols did not affect growth and yield in any of the crop species examined and therefore, seem to be ineffective as a growth enhancer. © 1998 Elsevier Science B.V.

Keywords: Ethanol; Methanol; C3 plants; Photorespiration; Yield enhancement; Chlorophyll content; Fluorescence

1. Introduction

Nonomura and Benson (1992) applied pure methanol and nutrient-supplemented methanol to the foliage of numerous C_3 crops under the warm and arid growing conditions of Arizona, and established marked increases in biomass production and water-use efficiency. Methanol is oxidized to formaldehyde and CO_2, and further synthesized into sugars and amino acids, including serine and methionine, in tissues of various C_3 plants (Cossins, 1964). Nonomura and Benson (1992), tried to determine the economic feasibility of methanol application as a carbon source for agricultural crops, but the resulting growth improvement far exceeded the expected effect of methanol as a foliar carbon nutrient. The enhanced growth

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following methanol application was not expressed in C_4 species. Phytotoxic symptoms were recorded when C_3 plants were not exposed to light after treatment. Addition of the glycine to the methanol solution enabled use of higher methanol concentrations without visible injuries. Nonomura and Benson (1992) concluded that utilization of methanol in plants is through a photorespiratory pathway; a non-beneficial pathway is used to detoxificate methanol and lost photosynthates are returned for use by the plant. This conclusion is supported by results from an earlier study, in which triacontanol (30 carbon alcohol) decreased photorespiration at very low concentrations in algae with C_3 characteristics (*Chlamydomonas reinhardtii*), while in algae with C_4 characteristics (*Anacystis nidulans*) no response was recorded (Haugstad et al., 1983).

Andrés et al. (1990) studied the effects of alcohols (methanol, ethanol, propanol, and butanol) on the association of the thylakoid membrane with fructose-1,6-bisphosphatase (FBPase), one of the principal enzymes controlling the activity of the photosynthetic carbon reduction cycle (Lawlor, 1987). Thylakoid-bound FBPase activity of pea (*Pisum sativum* L.) was increased, depending on the concentration and the length of the carbon chain of the alcohols (Andrés et al., 1990). The alcohol concentration required for maximum association decreased with increased chain length of the alcohol, being lowest with butanol and highest with methanol. Moderately concentrated (2–20%) alcohols stabilized the hydrophobic binding between FBPase and other membrane-bound proteins, probably due to the hydrophobic character of the alcohols, and increased FBPase activity (Andrés et al., 1990).

Hemming et al. (1995) measured metabolic heat rate, CO_2 production and O_2 uptake rates of bell pepper (*Capsicum annuum* L.) after exposing leaf tissue to methanol, and they noted an increase in carbon conversion efficiency which lasted several weeks. Even though carbon conversion efficiency was noticeably increased, methanol applications did not (data not reported) improve growth of tomato plants (*Lycopersicon esculentum* Mill.) (Hemming et al., 1995). Iersel et al. (1995) did not establish any positive effect of alcohol application on photosynthesis of field grown cotton (*Gossypium hirsutum* L.).

Alcohols have been shown to delay senescence of carnations (*Dianthus caryophyllus* L.), oat leaves kept in darkness (*Avena sativa* L.), and tomato epidermal pericarp discs, via inhibition of the effect of ethylene (Heins, 1980; Satler and Thimann, 1980; Saltveit, 1989). This delayed senescence could prolong the duration of high photosynthetic activity in leaves and increase CO_2 fixation and hence yield, especially if it occurred in the uppermost leaves during seed filling.

The article of Nonomura and Benson (1992) promoted great interest in the use of methanol and other alcohols as growth enhancers. Devlin et al. (1994) and Rowe et al. (1994) reported improved seedling growth of greenhouse grown tomato, pea, radish (*Raphanus sativus* L.) and wheat (*Triticum aestivum* L.) associated with foliar application of alcohol. Hartz et al. (1994), McGiffen et al. (1994), Wutcher (1994), Albrecht et al. (1995), Esensee et al. (1995), Feibert et al. (1995) and Iersel et al. (1995) did not, however, establish any positive effect on various crops, even though they followed the protocol of Nonomura and Benson (1992). A Finnish horticulture entrepreneur has been using methanol applications to increase growth and quality of greenhouse-grown roses. Frequent methanol applications reduce the requirement for fungicide applications to control rose mildew (*Sphaerotheca pannosa*) (Hantula, 1995, personal communication).

The main objectives of our experiments were to: (1) evaluate whether ethanol and methanol enhance growth of C_3 crops; (2) determine the efficacious alcohol concentration for foliar application; (3) determine the optimal application time and frequency; and (4) assess whether methanol, which is rather toxic, could be replaced with ethanol.

2. Materials and methods

2.1. Field trials

Field experiments were conducted at Viikki Experimental Farm, University of Helsinki, Finland

Table 1
Cultivars, N fertilizer application rates, treatments, and application time in field experiments

Experiment	Cultivars	N fertilization application rate (kg ha^{-1})	Treatments	Application time
Experiment I				
Barley	Inari	60	10% Ethanol	3–4 Leaf stage
	Kymppi	120	Control	Booting stage
	Pokko			Early grain filling
	Prisma			All three applications
Experiment II				
Oat	Salo	0	10% Ethanol	In oat and wheat same stage as in barley
Wheat	Satu	60	Control	
Pea	Pika	120		In pea and spring turnip rape at:
Spring turnip rape	Kulta			3–4 Leaf stage
				Flowering
				Seed filling
				All three applications
Experiment III				
Oat	Salo	80	20% Ethanol	In oat at:
Spring turnip rape	Kulta		40% Ethanol	4 Leaf stage
			20% Methanol	Booting stage
			40% Methanol	Both applications
			20% Ethanol + betaine	
			40% Ethanol + betaine	In spring turnip rape at:
			20% Methanol + betaine	3–4 Leaf stage
			40% Methanol + betaine	Flowering
			Betaine	Both applications
			Control	

(60°13′N) in 1994 and 1995. In 1994 two experiments were conducted: in the first experiment (I) the response of barley cultivars (*Hordeum vulgare* L.), and in the second (II) response of oat, wheat, pea, and spring turnip rape (*Brassica rapa oleifera* DC.), to foliar-applications of ethanol were studied. Crop cultivars, treatments, times of application, and nitrogen fertilizer application rates are given in Table 1. Experiment I was a split-plot with four replicates, for which timings of alcohol application were the main plots, and barley cultivars were split across them and experiment II was a completely randomized block with four replicates. The nitrogen fertilizer application rate was arranged in both experiments as a sub-experiment. There were three times of ethanol application and application rate was 10% ethanol with 0.1% surfactant (SITO: 99% alkylarylpoly–glycoether) at 200 l ha^{-1} in both experiments (Table 1).

In 1995 a third experiment (III) was conducted to study the response of oat and summer turnip rape to foliar-application of pure ethanol and methanol, and ethanol and methanol supplemented with glycine betaine at 2.5 kg/200 l ha^{-1} for oat and 0.5 kg/200 l ha^{-1} for summer turnip rape. Cultivars, treatments, application times, and nitrogen fertilization application rates are shown in Table 1. The experimental design was a split-plot with four replicates, for which times of application were the main plots, and different treatments were split across them. Oat and summer turnip rape were arranged as a sub-experiment in experiment III. Plants were sprayed twice,

Table 2
Cultivar, treatments, and application time in greenhouse experiments

Experiment	Cultivar	Treatments	Application time
Experiment IV			
Oat	Salo	20% Ethanol	4 Leaf stage
		30% Ethanol	Booting stage
		40% Ethanol	Both applications
		50% Ethanol	
		20% Methanol	
		30% Methanol	
		40% Methanol	
		50% Methanol	
		20% Ethanol + glycine (2 g/l)	
		20% Methanol + glycine (2 g/l)	
		Control	
Experiment V			
Oat	Salo	30% Ethanol	4 Leaf stage
		30% Methanol	
		30% Ethanol + glycine (2 g/l)	
		30% Methanol + glycine (2 g/l)	
		Control	

the second spraying followed seven days after the first (Table 1). Surfactant was added to all solutions at 0.5% (LI-700: 750 g l^{-1} soyal phospholipids).

In all three field experiments plot size was 10 m^2 (1.25 × 8 m with 12.5 cm between rows). Seeding rate was 120 viable seeds m^{-2} for pea, 350 viable seeds m^{-2} for spring turnip rape, 500 viable seeds m^{-2} for barley and oat, and 600 viable seeds m^{-2} for wheat. All plots were fertilized at sowing with NH_4NO_3. A mixture of MCPA and diklorpropp (DIPRO) at 2 l ha^{-1} was used to control weeds of cereals, and bentatsone (Basagran 480) at 2 kg ha^{-1} to control weeds in the pea crop. Dimethoate (R − Dimethoate) at 0.7 l ha^{-1} was used to control insects of spring turnip rape. Soil type was classified tentatively as clayey illitic Oxyaquic Cryoboroll. All alcohol applications were carried out with a hand-operated natural gas pressurized sprayer between 21.00 and midnight at 200 ml 10 m^{-2}.

Leaf chlorophyll was measured with a portable leaf chlorophyll meter (Minolta SPAD-502) on the second uppermost leaf from 20 plants per plot at 1, 3 and 7 days after ethanol application in experiment I. In experiment II leaf chlorophyll was measured on the second uppermost leaf of 40 plants 1, 2, 3, 4, and 7 days after ethanol application. Grain protein content was measured in experiment I using NIR-analysis. At 7 days after alcohol application (in 1995, 7 days after later application) plant samples were collected (2 × 0.5 m per plot) and dry weight of leaves, stems and heads were recorded. When cereal stands were yellow ripened, plant samples were collected from barley, oat, and wheat (3 × 0.5 m per plot) to determine total above ground phytomass, total weight of grains, harvest index (HI), and single kernel weight. Plots were harvested and grain yield and hectoliter-weight were measured.

2.2. Greenhouse trials

Experiments were conducted in the greenhouse at Viikki Experimental Farm, University of Helsinki, Finland (60°13′N) in the spring and summer of 1995. Oat (cv. Salo) was included in two experiments (IV and V). The treatments and times of alcohol application are shown in Table 2. The experimental design was a completely randomized block with four replications in experiment IV, and with five replications in experiment

V. Plants were top watered frequently in experiment IV, and surface watered in experiment V. In both trials 15 oat seeds were sown per 5-l pot containing fertilized peat and vermiculite (1:1). When seedlings emerged the number of plants per pot was thinned to ten. Alcohol (10 ml per pot) was applied with a battery-operated small-scale atomizer (Wagner Pico-Bel) between 09.00 and 12.00. Surfactant was added to all solutions (0.1% LI-700). A second alcohol application was given seven days after first application. To determine whether alcohol application caused stress reactions in oat, fluorescence was measured (with PSM Mark II) 24 hours after the first alcohol application and 1 h after the second application (experiment V). Leaf chlorophyll was measured 1, 2, 3 and 4 days after first alcohol application with a portable leaf chlorophyll meter (Minolta SPAD-502) in experiment V. At 7 days after the later application plants were collected and divided into main shoot and tillers and further split into leaves, stems, and heads, and dried overnight in oven at 100°C to determine their dry weights (both experiments).

2.3. Data analysis

Analysis of variance was carried out with Microsoft Excel 5.0 and Proc ANOVA and Proc GLM (SAS Institute, 1985) to determine the differences attributable to treatment effects for all measured traits (single kernel weight, above ground phytomass, fluorescence, total weight of grains, HI, leaf chlorophyll, number of grains per head, weights of heads, leaves and stems, and grain yield).

Table 3
Effect of 10% ethanol on grain yields of barley computed over N fertlizer application rate and cultivars in year 1994 (experiment I)

Application time	Yield (kg ha^{-1})	Tukey grouping[a]
Control	5283	a
Mid late	5164	ab
All three	5123	ab
Early	5070	ab
Late	5016	b

[a] Same letter at the column indicates no significant difference on the yield.

3. Results and discussion

We did not record any yield increases in our field experiments following alcohol applications to plant foliage (Tables 3–5), even though in both growing seasons (1994–1995) particularly high temperatures and low precipitation occurred during grain-filling. According to Nonomura and Benson (1992) such conditions should enhance the effect of methanol as a growth promoter. Ethanol applications slightly reduced the yield of barley cultivars in experiment I, when analysis of variance was computed over N fertilization rate and cultivars (Table 3). This slight reduction of yield could be due to a toxic effect of ethanol, discussed later, or it could be a mere coincidence. This latter is a more probably explanation, as in the other experiments no statistical differences in yield were recorded, and furthermore there were no differences in measured above-ground phytomass, weight of grains, harvest index (HI), and single kernel weight, between treatments (data not

Table 4
Effect of application time of 10% ethanol on grain and seed yield of oat (Salo), pea (Pika), spring turnip rape (Kulta), and wheat (Satu) computed over N fertilizer application rate in year 1994 (Experiment II)

Crop	Cultivar	Application time (Yield in kg ha^{-1})					
		Early	Mid late	Late	All three	Control	LSD (0.05)
Oat	Salo	6640	6715	6614	6798	6704	345.3
Pea	Pika	2329	2255	2363	2244	2133	480.2
Turnip rape	Kulta	1838	1891	1830	1812	1917	194.9
Wheat	Satu	5217	5328	5249	5254	5368	374.0

Table 5
Effect of application time of alcohol applications on grain and seed yield of oat (Salo), and spring turnip rape (Kulta) in year 1995 (Experiment III)

Application time	Treatment[a] (Yield kg ha^{-1})										
	1	2	3	4	5	6	7	8	9	10	LSD (0,05)
Oat											
Early	5239	5254	5621	5341	5586	5456	5479	5475	5626	5624	626.1
Mid late	5262	5366	5276	5417	5534	5492	5124	5331	5285	5416	587.3
Both	5343	5164	5179	5182	5365	5415	5244	5158	5356	5238	500.1
Turnip rape											
Early	1549	1518	1413	1422	1332	1322	1401	1572	1354	1450	466.0
Mid late	1505	1471	1353	1466	1458	1441	1600	1544	1402	1639	387.5
Both	1519	1492	1540	1453	1272	1395	1427	1389	1426	1420	294.5

[a]1, 20% ethanol; 2, 20% ethanol + betaine; 3, 40% ethanol; 4, 40% ethanol + betaine;5, 20% methanol; 6, 20% methanol + betaine; 7, 40% methanol; 8, 40% methanol + betaine; 9, betaine; and 10, control.

shown). When considering the high yields from the field trials (Tables 3–5), it seems likely that plants did not suffer significantly from any stress, despite high temperatures and low precipitation during grain-filling. In 1994, in particular, yields were so high that it would have been difficult to increase them further.

Alcohol was applied during late evening to obviate the effects of wind. It may be argued that absence of growth improvement in crops in the field was a result of the late application time—Nonomura and Benson (1992) applied methanol during the day. However, Finnish summer nights are light and there is no real dark period. Visible signs of toxicity should have been evident if plants were not able to metabolize alcohols. Furthermore, Cossins (1964), reported that methanol was utilized and converted to sugars and amino acids when applied to plant tissue in darkness. During evening hours air temperature is relatively low, which reduces evaporation of alcohol from the leaf surface and, thus, increases the possibility for alcohol to penetrate into the plant. This is especially important at high alcohol concentrations. Accordingly, it is likely that plants were able to convert the alcohol into other compounds in the field experiments, even though the applications were not carried out in high light intensity. It is also likely that the alcohol penetration into the plant is greater when application is conducted at lower temperatures, during the night.

In the greenhouse experiments (IV and V) the alcohol was applied during the sunny morning hours, but still no positive growth stimulation was recorded (data not shown). Furthermore, results of several other authors who applied methanol during the day to various agricultural and horticultural crops did not indicate enhanced growth and increased yield, is accordance with our findings (Hartz et al., 1994; McGiffen et al., 1994; Wutcher, 1994; Albrecht et al., 1995; Esensee et al., 1995; Feibert et al., 1995; Iersel et al., 1995).

Cossins (1964) showed that methanol is mainly converted to CO_2, which probably can be used as a source of carbon in plants. In our study, and in those cited above, the quantities of alcohol applied to the plants were, however, so small, when compared with carbon fixation of the plant canopy during growing season, that it cannot be expected that changes in growth, resulting from alcohol application, would be registered if the alcohol is merely a carbon source. Moreover, it is not clear to what extent the alcohol is absorbed and utilized in the plant. Probably a large proportion of alcohol is lost via evaporation, especially when applied on a sunny, warm day. Furthermore, Cossins (1964) observed large variation in utilization of methanol when feeding it to different cell tissue of various crop species. Over 90% utilization was noted in carrot root tissue, whereas pea cotyledons utilized only slightly over

Table 6
Effect of alcohol applications on leaf chlorophyll content (indicated as SPAD-value) of oat (Salo) (Experiment V)

Treatment	Days from application (SPAD-value)[a]							
	1		2		3		4	
30% Ethanol	39.95	c	43.03	a	42.84	a	42.15	ab
30% Methanol	43.00	a	43.35	a	43.67	a	43.46	a
30% Ethanol + glycine	41.95	abc	43.16	a	43.37	a	42.82	ab
30% Methanol + glycine	42.33	ab	43.29	a	42.41	a	41.59	b
Control	40.98	bc	42.49	a	43.12	a	42.42	ab
		**		ns		ns		*

[a]Same letter at the column indicates no significant difference on the SPAD-value according to Tukey test.

10%. Unfortunately, in the study of Cossins (1964) the same organs from different species were not compared.

Leaf chlorophyll concentrations were measured to determine if alcohols cause any breakdown of the leaf chlorophyll proteins, and to establish the potential growth impulse. In both cases the chlorophyll content should be lower in plants treated with alcohol compared with control plants. There were some significant differences in measured chlorophyll values arising from nitrogen level, time of application, and treatment (data not shown). Increasing nitrogen fertilization resulted in increased leaf chlorophyll values, which fluctuated according to application times (from seedling to grain filling). There were, however, no clear persistent trends associated with alcohol applications affecting leaf chlorophyll content; ranking of treatments varied between application times. Similar results were obtained in experiment V. In the greenhouse, alcohol–ethanol in particular—supplemented with glycine, slightly increased the SPAD-values, whereas the alcohols without any amino acid supplement did not affect chlorophyll content (Table 6). Therefore, the slight increase in SPAD-values is probably due to the glycine alone rather than the interaction of the alcohol and glycine. As there were no visible injuries caused by alcohol application, fluorescence was measured in the greenhouse experiment to determine whether alcohol applications caused internal, temporary disturbance to the photosynthetic reaction chain (experiment V). Ethanol and methanol at concentrations of 30% did not affect the capacity of the electron transfer chain (Table 7).

Ethanol and methanol were supplemented with glycinebetaine in experiment III. Exogenous application of glycinebetaine has been shown to increase drought stress tolerance and increase biomass production and yield in drought stressed maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) (Agboma et al., 1997). Differencies between pure alcohol solutions, alcohols supplemented with glycinebetaine and control were, however, not established in yield (Table 5) or in any of the physiological traits measured (data not shown) in oat and spring turnip rape.

Phytotoxicity was not noticed in the field trials, even though the applications were carried out late in the evening, nor in the experiments carried out in greenhouse, where high alcohol concentrations were used (up to 50%). Alcohols are toxic to plant tissue, causing necrotic lesions to develop, and therefore they have to be converted rapidly to non-toxic compounds. Nonomura and Benson

Table 7
Effect of alcohol applications on fluorescence of oat (Salo) (Experiment V)

Treatment	Fluorescence (hours from application)	
	1	24
30% Ethanol	0.710	0.741
30% Methanol	0.721	0.737
30% Ethanol + glycine	0.718	0.741
30% Methanol + glycine	0.732	0.740
Control	0.709	0.733
LSD (0.05)	0.024	0.030

(1992) recorded symptoms of phytotoxicity when treated plants were shaded over 24 h, when methanol application was repeated several times in low light conditions, and when plants were treated with too high a concentration of methanol. Nonomura and Benson (1992) suggested, that metabolism of methanol in C_3 plants requires photorespiration and presence of glycine, one of the products of the photorespiratory cycle. C_3 plants may lose 30% of fixed carbon during photorespiration, even under optimal growing conditions (Lawlor, 1987).

Toxicity of alcohol depends on the plant species being treated and the anatomical target of application. According to Nonomura and Benson (1992) trunk sections of various trees could withstand high concentrations of methanol (up to 100%), whereas for cereals 20% methanol was the optimal concentration to promote growth. The concentration of methanol applications was set at 10% below established toxicity level by Nonomura and Benson (1992). Rowe et al. (1994) noticed that low concentrations (10%) of ethanol and methanol were deleterious to tomato, when applied to roots, whereas aerial plant parts withstood higher concentrations. Hemming et al. (1995) observed a similar response on leaf and root tissues of tomato. In contrast to the results of Nonomura and Benson (1992) no damage was observed when oat seedlings were treated with ethanol and methanol at concentrations up to 50% in experiment IV. Similarly, Albrecht et al. (1995) reported that pea and winter wheat were able to tolerate extremely high methanol concentrations (up to 80–90%) without any evidence of severe toxification.

Alcohols have been shown to affect the photosynthetic pathway of C_3 plant tissues in a controlled laboratory environment (Andrés et al., 1990; Hemming et al., 1995), increase seedling growth in a greenhouse environment (Devlin et al., 1994; Rowe et al., 1994), and increase growth and yield of various crops under field conditions (Ries et al., 1978; Prasad and Prasad, 1990; Nonomura and Benson, 1992). Alcohols have also been shown to retard senescence (Heins, 1980; Satler and Thimann, 1980; Saltveit, 1989), which prolongs the duration of active photosynthesis in leaves, possibly improving CO_2 fixation and thereby increases biomass production.

Even though there is some evidence of the beneficiality of alcohol treatments, the mode of action of alcohols on photosynthesis and photorespiration is still obscure and such effects reported by Nonomura and Benson (1992) seem very difficult to reproduce. The potential promoting effect on photosynthesis and growth seems to vanish in the field conditions and no improvement in growth and yield has been reported, as in this study and many other studies cited in this paper (Hartz et al., 1994; McGiffen et al., 1994; Wutcher, 1994; Albrecht et al., 1995; Esensee et al., 1995; Feibert et al., 1995; Iersel et al., 1995).

Improved recovery from drought after ethanol and methanol application was recorded (seedling growth of tomato increased 5 to 50%, data not shown) from a small-scale preliminary experiment carried out in the greenhouse. Alcohol treatments did not have any positive effect on seedling growth under optimium watering or continious drought stress situation (data not shown). Under severe water stress conditions alcohols might function as a osmoprotectants, which protect plants' vital processes and enable quick recovery when the stress is removed. Another possible explanation for the positive response could be that alcohols block the senescencing effect of ethylene in stressed plants and therefore improve recovery. Further studies are being conducted to reveal more precisely the effect of alcohols on stressed plants.

4. Conclusion

In conclusion, on the basis of this study, alcohol applications do not seem to have any growth promoting effect on the C_3 crops studied in Finnish growing conditions.

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