

RESEARCH PAPERS

# Differences in Photosynthesis and Terpene Content in Leaves and Roots of Wild-Type and Transgenic *Arabidopsis thaliana* Plants<sup>1</sup>

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**Abstract**—We investigated the hypotheses that two different varieties of *Arabidopsis thaliana* show differences in physiology and terpene production. The two varieties of *A. thaliana* used in this study were wild-type (WT) and transgenic line (*CoxIV-FaNES I*) genetically modified to emit nerolidol with linalool/nerolidol synthase (COX). Photosynthetic rate, electron transport rate, fluorescence, leaf volatile terpene contents and root volatile terpene contents were analyzed. For both types, we found co-eluting  $\alpha$ -pinene+ $\beta$ -ocimene, limonene, and humulene in leaves; and in the roots we found co-eluting  $\alpha$ -pinene+ $\beta$ -ocimene, sabinene+ $\beta$ -pinene,  $\beta$ -myrcene, limonene, and humulene. At the end of the growing cycle, COX plants tended to have lower pools of terpene compounds in their leaves, with 78.6% lower photosynthesis rates and 30.8% lower electron transport rates, compared with WT plants at that time. The maximal photochemical efficiency  $F_v/F_m$  was also significantly lower (25.5%) in COX plants, indicating that these varieties were more stressed than WT plants. However, COX plants had higher (239%) root terpene contents compared to WT plants. COX plants appear to favor root production of volatile terpenes rather than leaf production. Thus we conclude that there were significant differences between COX and WT plants in terms of terpenoid pools, stress status and physiology.

**Keywords:** *Arabidopsis thaliana*, *FaNES I*, leaf terpene contents, root terpene contents, photosynthesis

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## INTRODUCTION

Plants produce a variety of volatile organic compounds (VOCs) of which isoprenoids are the most representative and abundant group [1]. Mono- and sesquiterpenes are C10 and C15 isoprenoid compounds that can be produced in the chloroplasts (MEP pathway) and in the cytosol (MVA pathway) [2]. One of the generally accepted physiological functions of these isoprenoids is to avoid damage in cellular membranes when the plants are under physiological stresses, for example, water stress, high temperatures, oxidative stress and high irradiation [3]. Mono- and sesquiterpenes also have ecological functions; they contribute to the defense strategies of the plants against pathogen attack [4], they can act as pollinator attractants [1], and may also play a role in allelopathy [5]. Terpenoids can also have impact on regional air quality reacting with anthropogenic and biogenic nitrogen oxides,

contributing to tropospheric ozone and photochemical smog formation [6].

Volatile isoprenoids are mostly produced and emitted by the aerial parts of the plant (leaves and flowers). However, Janson et al. [7] suggested roots as a possible source of monoterpenes in soil and studies also show that there is terpenoid production and emission in roots [8]. This has been supported by measurements of monoterpene emissions in laboratory experiments from pine roots with qualitative and quantitative evidence of the existence of monoterpenes in soils under pine trees [9]. Root emitted terpenes have an ecological role in plant-animal interactions; for example, nematodes are attracted to emission of (E)- $\beta$ -caryophyllene from western corn maize roots damaged by rootworm [10].

*Arabidopsis thaliana* flowers produce and emit terpenes [11, 12]. This species is thought to have over 30 putative genes associated with terpene synthases (TPSs), a multigene family [12, 13]. Most of them are almost exclusively expressed in flowers [12, 14, 15].

Other parts of *A. thaliana* are likely to produce and emit terpenes: trace amounts of the monoterpenes limonene and  $\beta$ -myrcene were emitted within its leaves [12],  $\beta$ -ocimene was emitted by rosette leaves [16] and even a release from roots to the rhizosphere (namely, 1,8-cineole) was suggested [17]. Although

<sup>1</sup> The article is published in the original.

**Abbreviations:** A—CO<sub>2</sub> uptake; COX—transgenic line (*CoxIV-FaNES I*); ETR—electron transport rate;  $F_v/F_m$ —maximum photochemical efficiency of PSII;  $F/F_m'$ —actual photochemical efficiency of PSII;  $g_s$ —stomatal conductance; TPSs—terpene synthases; VOCs—volatile organic compounds; WT—wild-type.

Chen et al. [12] reported leaf and root emissions, there is generally a lack of information regarding leaf or root production of terpenes in this species.

Recent studies show wide genetic variation among *A. thaliana* from diverse habitats. Different varieties of this species are likely to have different genotypes that might affect both primary and secondary metabolism [18]. We aimed to test the prediction that different *Arabidopsis* varieties will show differences in physiology and terpene content in leaves and roots. The two selected varieties were a wild-type (WT) and a transgenic line (*CoxIV-FaNES 1*) with linalool/nerolidol synthase, targeted specifically to the mitochondria (COX) developed by Kappers [19]. These varieties were selected as contrasting types with high potential to display such differences.

## MATERIALS AND METHODS

**Plant material and plant growth.** We used 15 specimens each of *Arabidopsis thaliana* ecotype *Landsberg erecta* (*Ler-0*) (WT) and the transgenic ecotype *Columbia CoxIV-FaNES 1* line (COX) supplied by Iris Kappers (Wageningen UR, Plant Research International, Netherlands), which expresses a linalool/nerolidol synthase gene. The seeds were germinated for 4 days at 4°C in Petri dishes, and were cultivated in 475 cm<sup>3</sup> plastic pots filled with peat and perlite (2 : 1, v/v) in a controlled environment chamber (14-h photoperiod, 130–150 μmol quanta/(m<sup>2</sup> s), 21°C air temperature).

The growth medium used was based on that optimized by Gibeaut et al. [20]. The final contents were 1.5 mM Ca(NO<sub>3</sub>)<sub>2</sub>, 1.25 mM KNO<sub>3</sub>, 0.75 mM MgSO<sub>4</sub>, 0.5 mM KH<sub>2</sub>PO<sub>4</sub>, 70 μM Fe-diethylenetriamine pentaacetate, 50 μM KCl, 50 μM H<sub>3</sub>BO<sub>3</sub>, 10 μM MnSO<sub>4</sub>, 2 μM ZnSO<sub>4</sub>, 1.5 μM CuSO<sub>4</sub>, and 0.075 μM ammonium molybdate (chemicals were from Fluka, Buchs, Switzerland).

**Plant measurements: basal rosette diameter, CO<sub>2</sub> exchange and chlorophyll fluorescence.** The diameter of the basal rosette was measured in each of the 30 plants 5 times throughout the experiment at 15, 18, 22, 28 and 31 days after germination respectively. CO<sub>2</sub> uptake (*A*) and stomatal conductance (*g<sub>s</sub>*) were measured in leaves of the basal rosette only at the end of the growing cycle 31 days after germination of the seeds, using a portable non-dispersive infra-red gas analyzer (IRGA), model ADC-LCi (ADC Inc. Hoddesdon, Hertfordshire, England) connected to an Arabidopsis leaf chamber (ADC Inc. Hoddesdon, Hertfordshire, England). *A* and *g<sub>s</sub>* values were expressed on a projected leaf area basis, which was measured with Li-Cor 3100 Area Meter (Li-Cor, United States).

The maximum photochemical efficiency of PSII ( $F_v/F_m$ ) and the apparent photosynthetic electron transport rate (ETR) were also measured at the end of the growing cycle with a PAM-2000 fluorometer (Walz, Germany). ETR was estimated as:

$$\text{ETR} = \Delta F/F_m' \times \text{PPFD} \times 0.84 \times 0.5,$$

where  $\Delta F/F_m'$  (actual photochemical efficiency of PSII) was calculated within the software, 0.84 is the coefficient of absorption of the leaves, and 0.5 is the fraction of electron involved in the photoexcitation produced by one quanta [21]. Chlorophyll fluorescence was measured twice: after turning the lights on and after 7 h of lighting. The maximum PSII photochemical efficiencies ( $F_v/F_m$ ) were measured after keeping leaves in the dark for at least 25 min.

**Laboratory analyses: leaf and root terpene contents at the end of the growth cycle.** Samples for terpene extractions were taken from leaves and roots 35 days after germination, from the plants growing in the controlled environmental chamber. Leaf and root material was ground in liquid nitrogen and repeatedly extracted (three times) with pentane, with a non-terpenoid internal standard (0.1 μL dodecane). The pentane-extracted leaves and roots were centrifuged at 10000 rpm for 10 min. Extracts were then concentrated with a stream of nitrogen, because low concentrations were expected.

Monoterpene separation was conducted using a GC-MS system (Hewlett Packard HP59822B, United States). Extracts (3 μL) were injected into the GC-MS system and passed into a 30 m × 0.25 mm × 0.25 mm film thickness capillary column (Supelco HP-5, Crosslinked 5% pH Me Silicone). A full scan method was used to perform the chromatography. The GC oven was programmed to start at 40°C, then the temperature was increased at 30°C/min up to 70°C, and thereafter at 10°C/min up to 150°C, when the temperature was maintained for 5 min, and thereafter at 70°C/min up to 250°C, which was maintained for another 5 min. Helium flow was 1 mL/min. For both varieties of *A. thaliana*, two blank analyses per day were also conducted.

The identification of terpenes was conducted by comparison with standards from Fluka (Buchs, Switzerland), and with the GCD Chemstation G1074A HP with the Wiley275 library. The internal standard dodecane was used to determine extraction efficiency. Dodecane did not co-elute with any terpene. Calibrations was performed with the common terpenes α-pinene, 3-carene, β-pinene, β-myrcene, p-cymene, limonene, and sabinene standards once every five analyses. The quantification of the terpenes was conducted using the fractionation product with mass 93 [22]. Terpene calibration curves (*n* = 4 different terpene contents) were always significant (*R*<sup>2</sup> > 0.99) in the relationship between signal and terpene contents. The most abundant terpenes had very similar sensitivity (differences were less than 5%). Total terpene contents were calculated as the sum of these main terpenes.

Leaf and root dry weights were determined after drying the plant material at 60°C until constant weight in each of the 30 plants at the end of the growing cycle 31 days after germination of the seeds.

**Statistical analyses.** Analysis of variance (ANOVA) with Fisher post hoc tests for all the stud-

**Table 1.** Basal rosette diameter (cm) evolution for wild-type (WT) and transformed (COX) *A. thaliana* plants after germination

Days after germination	WT	COX	<i>P</i> -values
15	4.16 ± 0.32	4.01 ± 0.65	0.83 (ns)
18	4.14 ± 0.25	4.27 ± 0.71	0.85 (ns)
22	4.60 ± 0.32	4.64 ± 0.70	0.86 (ns)
28	4.71 ± 0.36	5.81 ± 0.68	0.015 *
31	4.72 ± 0.35	6.33 ± 0.55	0.0051 **

Statistical significance for the effect of variety is indicated (WT *n* = 15, COX *n* = 15); ns—not significant, \**P* < 0.05, \*\**P* < 0.01.

ied dependent variables, and Student's *t*-tests were used to test the significance of differences in response between transformed (COX) and wild-type plants (WT), using R 2.7.2 software for Windows (R Foundation for Statistical Computing, Vienna, Austria). Differences were considered significant at a probability level of *P* < 0.05.

## RESULTS

### *Growth: Mean Diameter of the Basal Rosette*

The growing pattern of WT and COX varieties differed: at the end of the experiment COX plants achieved 34% larger basal rosettes compared with WT plants (Table 1). WT plants reached their maximum diameter half way through the experiment, with very low increase during the two last weeks. During this time WT plants increased from 4.16 to 4.72 cm. COX plants had larger basal rosettes diameters that increased continuously during the 4 weeks of the experiment. During the two last weeks of the experiments, COX plants grew from 4.0 to 6.3 cm (Table 1).

### *Plant Biomass*

The dry weight of the aerial part of the plants was significantly higher in WT (0.082 ± 0.009 mg) compared with COX plants (0.054 ± 0.007 mg) (Table 2). The dry weight of the roots was significantly lower in

WT (0.056 ± 0.009 mg) compared with COX plants (0.141 ± 0.06 mg) (Table 2).

### *Net Photosynthetic Rates, Stomatal Conductance and Fluorescence Measurements at the End of the Growth Cycle*

Net photosynthetic rates at the end of the experiment (*A*) were 78.6% lower in COX plants than in WT plants (*P* < 0.001; Table 2). Stomatal conductance (*g<sub>s</sub>*) tended to be lower in COX plants compared to WT plants (not significant *P* = 0.12, Table 2). The apparent photosynthetic electron transport rate (ETR) was 30.8% lower (*P* < 0.001) in COX plants than in WT plants (Table 2). The maximum photochemical efficiency of PS II (*F<sub>v</sub>/F<sub>m</sub>*) was 25.5% lower (*P* < 0.001) in COX plants than in WT plants (Table 2).

### *Leaf Terpene Contents*

For both varieties, leaves contained α-pinene+β-ocimene (WT—42.67 ± 20.64 μg/g dry wt, COX—10.55 ± 2.45 μg/g dry wt), limonene (WT—24.64 ± 6.73 μg/g dry wt, COX—11.58 ± 2.81 μg/g dry wt) and humulene (WT—10.64 ± 5.76 μg/g dry wt, COX—34.31 ± 7.65 μg/g dry wt) (Fig. 1, Table 3).

There was no significant difference in leaf terpene contents between the two varieties, but there was a tendency for higher terpene contents in WT plants (Fig. 2). Other unidentified compounds were found: “unidentified compound 1” (possibly myrtenal), “unidentified compound 2” (possibly β-ionone) and “unidentified compound 3” (Fig. 1, Table 3). COX plants tended to produce lower amounts of terpenes than WT plants (Fig. 1). The “unidentified 2” compound was not produced in COX plants (Fig. 1).

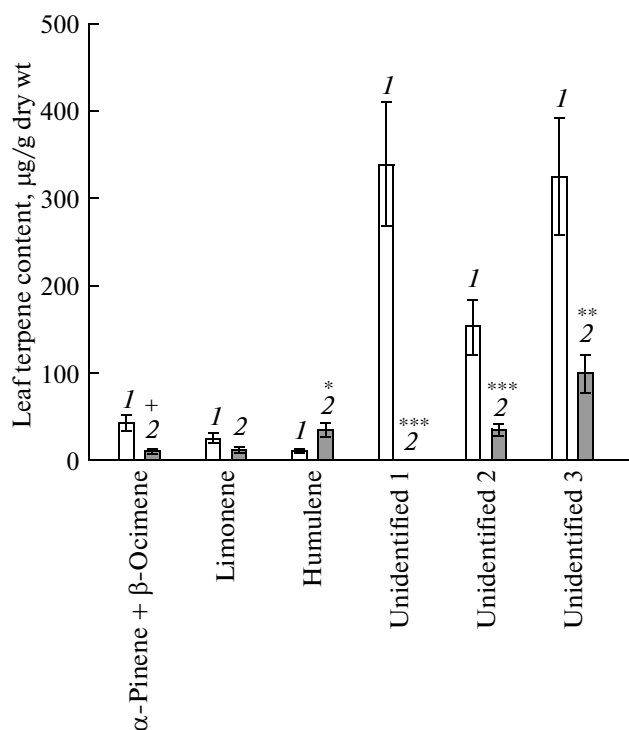
### *Root Terpene Contents*

For both varieties, roots contained α-pinene + β-ocimene (WT—9.5 ± 1.32 μg/g dry wt, COX—21.58 ± 3.61 μg/g dry wt), sabinene + β-pinene (WT—32.16 ± 3.66 μg/g dry wt, COX—100.91 ± 15.34 μg/g dry wt), β-myrcene (WT—0 ± 0 μg/g dry wt, COX—23.44 ± 5.95 μg/g dry wt), limonene (WT—2.35 ± 1.25 μg/g dry wt, COX—16.75 ± 2.56 μg/g dry wt) and humulene

**Table 2.** Leaf and root weights, net photosynthetic rates, stomatal conductance, apparent photosynthetic electron transport rate and photochemical efficiency (*F<sub>v</sub>/F<sub>m</sub>*) for wild-type (WT) and transgenic (COX) *A. thaliana* plants 35 days after germination

Variables	Units	WT	COX	<i>P</i> -values
Leaf weight	mg dry wt	0.082 ± 0.009	0.054 ± 0.007	<0.05
Root weight	mg dry wt	0.056 ± 0.009	0.141 ± 0.060	<0.05
Net photosynthetic rates	μmol/(m <sup>2</sup> s)	1.58 ± 0.17	0.96 ± 0.17	<0.001
Stomatal conductance	mol/(m <sup>2</sup> s)	0.036 ± 0.001	0.030 ± 0.001	ns (0.12)
Electron transport rate	μmol/(m <sup>2</sup> s)	0.55 ± 0.02	0.47 ± 0.02	<0.001
<i>F<sub>v</sub>/F<sub>m</sub></i>		0.70 ± 0.01	0.53 ± 0.03	<0.001

Statistical significance for the overall effect of variety is indicated (WT *n* = 15, COX *n* = 15); ns—not significant.



**Fig. 1.** Individual foliar contents of identified and unidentified terpenes for wild-type (WT, 1) and transgenic (COX, 2) *A. thaliana* plants 35 days after germination. Vertical bars indicate standard errors of the mean (WT  $n = 15$ ; COX  $n = 15$ ). Significant differences among varieties are indicated (+  $P < 0.1$ , \*  $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*  $P < 0.001$ ).

(WT— $5.44 \pm 1.45$  µg/g dry wt, COX— $2.97 \pm 1.34$  µg/g dry wt) (Fig. 3, Table 3).

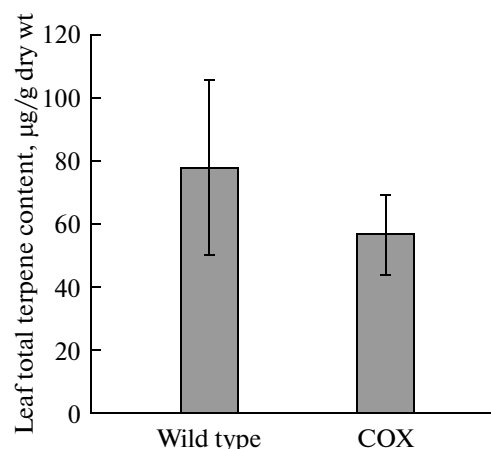
COX plants showed significantly ( $P < 0.001$ ) higher (239%) contents of terpenes compared with WT plants (Fig. 4). Other terpenes were found: “unidentified 3” and “unidentified 4” (Fig. 3, Table 3).

## DISCUSSION

### Compounds Detected in Leaf and Root Extracts

There is clear evidence of terpene production in leaves and roots of both WT and COX varieties of *A. thaliana*. Our results agree with and expand the previous results who found traces of terpenes in leaves of *Arabidopsis thaliana* plants, such as β-caryophyllene, thujopsene, β-farnesene, and β-chamigrene [12, 23].

We did not find linalool, nerolidol or DMNT ((E)-4,8-dimethyl-1,3,7-nonatriene) in the foliage and root extracts of the COX plants as it was expected. Based on previous findings differences in the outcome of linalool/nerolidol synthase could be due to allelic variation in encoding functional terpene synthase genes, conversion of the enzyme product into other compounds as found by Aharoni et al. [11], differences in subcellular sites of gene expression, different activities of the terpene synthase together with different substrate pools available for the enzyme might be



**Fig. 2.** Total leaf terpene contents for wild-type and transgenic (COX) *A. thaliana* plants 35 days after germination. “Total” only includes the identified terpenes α-pinene + β-ocimene, limonene, and humulene. Vertical bars indicate standard errors of the mean (WT  $n = 15$ ; COX  $n = 15$ ).

responsible for the product outcome [11, 14], or silent metabolism [24]. It is possible that no linalool or nerolidol was produced; in fact, Kappers et al. [19] detected no linalool emissions from any of their plants’ foliage, and no nerolidol in 25% of the transformed (COX) plants. It is also possible that linalool might have been produced in leaves but released immediately after production (similar to isoprene). It is also possible that our extraction technique would not have captured such compounds. The most likely possibility is that most of linalool and nerolidol are produced in *Arabidopsis* flowers, but we did not investigate floral emissions because we removed the flowers to retard the senescence processes in the leaves [25]. Aharoni et al. [11] found small amounts of linalool (from 0.02 to 13.3 µg/day plant depending on the transgenic line) in the headspace of transformed *Arabidopsis* plants, with the *FaNES1* gene expressed in the plastids, while Kappers et al. [19] expressed the *FaNES1* gene in the mitochondria and also observed nerolidol emissions from the transformed plants’ foliage. Kappers et al. [19] did not make clear in which plastids the gene was expressed. If it was only in the chloroplasts, then the compounds detected in the root are likely to have been synthesised in the chloroplasts and differentially translocated down to the roots. However Hedtke et al [26] indicate that target plastids might be both chloroplasts and non-pigmented leucoplasts in the roots. In which case, the root terpene content is likely to be synthesised within the root tissue. Further experimentation is needed to confirm this. But in any case, lack of nerolidol and linalool does not detract in any way from the aims and conclusions of this work.

### Effect of Variety

There were differences in the morphology of the basal rosette in the two varieties used in our study. The

**Table 3.** Retention time and most abundant ions (m/z) for the main terpenes found in leaves and roots

Compound	Tissue	Retention time, min	Most abundant ions	Type of terpene
$\alpha$ -Pinene/ $\beta$ -ocimene	Leaf, root	7.79	93.00 (28%), 90.95 (9.05%), 92.00 (8.51%), 27.05 (4%)	Monoterpene
Sabinene/ $\beta$ -pinene	Root	9.18	94.00 (12.95%), 93.15 (12.39%), 41.05 (9.65%), 28.05 (7.22%), 31.10 (7.21%)	Monoterpene
$\beta$ -Myrcene	Root	9.69	105.00 (10.55%), 93.10 (7.40%), 31.00 (6.72%), 119.95 (5.03%), 55.00 (5.01%)	Monoterpene
Unidentified 4	Root	10.26	43.10 (34.34%), 107.95 (14.11%), 150.00 (11.36%), 41.00 (9.89%), 92.90 (1.02%)	Monoterpene
Limonene	Leaf	10.47	68.05 (7.07%), 67.05 (5.01%), 93.00 (5.43%), 43.05 (5%), 57.05 (4.14%)	Monoterpene
Unidentified 1 (possibly myrtenal)	Leaf	15.00	79.00 (6.53%), 28.00 (5.93%), 107.00 (5.88%), 90.95 (5.17%), 93.10 (3.58%)	Monoterpene
$\alpha$ -Humulene (leaf)	Leaf, root	16.22	93.00 (21.39%), 80.00 (7.15%), 121.05 (5.54%), 91.00 (4.44%), 92.10 (4.35%)	Sesquiterpene
Unidentified 2 (possibly $\beta$ -ionone)	Leaf	16.53	177.00 (20.69%), 43.00 (12.44%), 122.95 (12.21%), 135.00 (3.35%), 93.00 (1.64%)	Sesquiterpene
Unidentified 3	Leaf, root	17.40	149.00 (43.49%), 176.95 (9.05%), 150.00 (5.11%), 175.95 (3.82%), 93.00 (2.2%)	Sesquiterpene

WT had higher numbers of smaller leaves that were shed and replaced when they reached a certain size, while the COX species had fewer leaves whose length increased constantly along the vegetative cycle. Despite the fact that the two varieties (WT and COX) are morphologically different, the experimental plants were comparable in terms of health and phenology to satisfy the aims of the experiment, providing two different varieties of the same species.

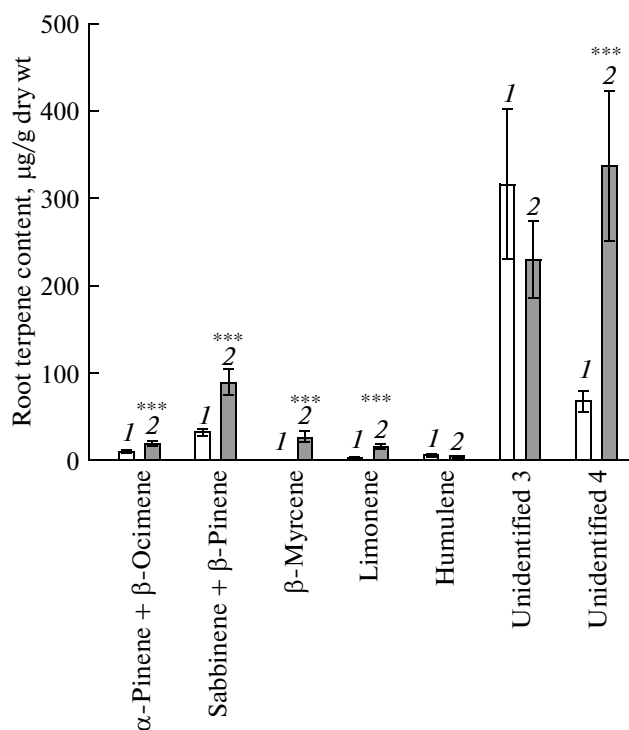
There were differences in growth in both varieties of *Arabidopsis*. WT plants reached their maximum diameter before the COX plants (Table 1). The COX plants' diameters increased gradually and consistently from the germination until the mature state. Kappers et al. [19] also found that first- and second-generation COX plants showed some growth retardation of the basal rosette. Other differences in growth of *Arabidopsis* varieties have been previously reported: Beemster et al. [27] found that growth of roots varied substantially between varieties.

Different varieties of *A. thaliana* showed evidence of differences in primary and secondary metabolism, indicating that metabolism in the two varieties is affected either by their different genotype, or by different post-translational control of metabolic processes. At the end of the experiment (21 days after germination), COX plants showed lower photosynthetic activity and production in leaves than the WT plants. Com-

paring COX and WT plants, we found that stomatal conductance (Table 2) and calculated electron transport rates (ETR) were lower in COX plants than in WT, and this appeared to result in lower photosynthesis rates (Table 2). These results might indicate that the COX plants were more stressed than WT plants. In addition, the mean ratio  $F_v/F_m$  was significantly lower in COX plants compared with WT, which also indicates that the COX plants might have been suffering a degree of stress at the end of the experiment [28], although the plants were grown in identical conditions (see MATERIALS AND METHODS section).

COX plants presented lower leaf weight than WT plants but higher root weight (Table 1). These plants, under stress conditions may reallocate carbon from its leaves towards its roots. Reallocation of primary compounds within the plant was shown to reflect a strategy to survive the damaging effects of herbivores [29]. Previous authors have shown that stressed plants could be characterized by high terpene biosynthesis in roots [10]. Rasmann et al. [10] showed that production and emission of root terpenes in maize plants is related to indirect defense by attracting entomopathogenic nematodes.

The carbon reallocation theory is supported by terpene foliar and root productions (Figs. 2 and 4): there was a tendency for COX plants to have lower foliar terpene contents than the WT plants, though this difference was not significant, and root terpene contents



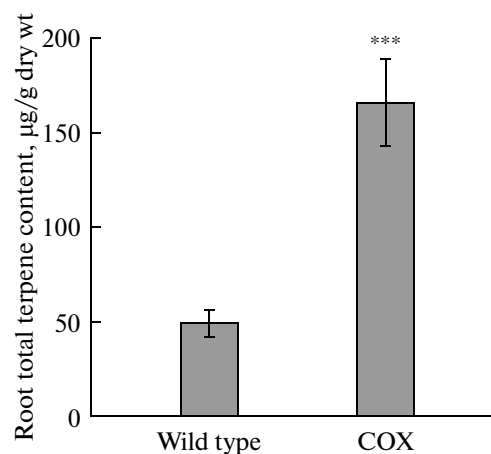
**Fig. 3.** Individual root contents of identified and unidentified terpenes for wild-type (WT, 1) and transgenic (COX, 2) *A. thaliana* plants 35 days after germination. Vertical bars indicate standard errors of the mean (WT  $n = 15$ ; COX  $n = 15$ ). Significant differences among varieties are indicated (\*\*\*)  $P < 0.001$ .

were much higher in COX plants than in WT plants. Basyuni et al. [30] found that leaf isoprenoid contents generally declined while root contents increased in salt-stressed mango plants. In our study, the same relationship of lower leaf terpene contents and higher root terpene contents in the COX plants also reflects the higher stress status in the COX plants, as indicated by the lower  $F_v/F_m$  values.

#### Concluding Remarks

We have shown that a modified *Arabidopsis* variety (which emits nerolidol from mitochondrial synthesis) directs resources towards root production of terpenes rather than leaf production of these compounds. These plants also have generally lower carbon assimilation rate at the end of the growth cycle compared with wild-type plants.

Further work of a similar nature is needed on other plant species, particularly root crop species that have been genetically modified or bred for certain characteristics of pest resistance and productivity. Breeding or genetic modifications resulting in redirection of resources to root production of terpenes might be advantageous for the defence strategies of root crops against soil herbivores and pathogens. However, the



**Fig. 4.** Total root terpene contents for wild-type and transgenic (COX) *A. thaliana* plants 35 days after germination. “Total” includes  $\alpha$ -pinene +  $\beta$ -ocimene, sabinene +  $\beta$ -pinene,  $\beta$ -myrcene, limonene, and humulene. Vertical bars indicate standard errors of the mean (WT  $n = 15$ ; COX  $n = 15$ ). Significant differences among varieties are indicated (\*\*\*)  $P < 0.001$ .

associated lower carbon assimilation might adversely affect root crop yield.

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#### REFERENCES

1. Kesselmeier, J. and Staudt, M., Biogenic volatile organic compounds (VOC): an overview on emission, physiology and ecology, *J. Atmos. Chem.*, 1999, vol. 33, pp. 23–88.
2. Owen, S.M. and Peñuelas, J., Opportunistic emissions of volatile isoprenoids, *Trends Plant Sci.*, 2005, vol. 10, pp. 420–426.
3. Penuelas, J. and Llusia, J., Bvocs: plant defense against climate warming? *Trends Plant Sci.*, 2003, vol. 8, pp. 105–109.
4. Pichersky, E. and Gershenzon, J., The formation and function of plant volatiles: perfumes for pollinator attraction and defense, *Curr. Opin. Plant Biol.*, 2002, vol. 5, pp. 237–243.
5. Peñuelas, J., Ribas-Carbo, M., and Giles, L., Effects of allelochemicals on plant respiration and oxygen isotope

- fractionation by the alternative oxidase, *J. Chem. Ecol.*, 1996, vol. 22, pp. 801–805.
6. Chameides, W.L., Lindsay, R.W., Richardson, J., and Kiang, C.S., The role of biogenic hydrocarbons in urban photochemical smog – Atlanta as a case-study, *Science*, 1988, vol. 241, pp. 1473–1475.
  7. Janson, R.W., Monoterpene emissions from Scots pine and Norwegian spruce, *J. Geophys. Res.*, 1993, vol. 98, pp. 2839–2850.
  8. Asensio, D., Peñuelas, J., Filella, I., and Llusà, J., On-line screening of soil VOCs exchange responses to moisture, temperature and root presence, *Plant Soil*, 2007, vol. 291, pp. 249–261.
  9. Asensio, D., Owen, S.M., Llusà, J., and Peñuelas, J., The distribution of volatile isoprenoids in the soil horizons around *Pinus halepensis* trees, *Soil Biol. Biochem.*, 2008, vol. 40, pp. 2937–2947.
  10. Rasmann, S., Kollner, T.G., Degenhardt, J., Hiltbold, I., Toepfer, S., Kuhlmann, U., Gershenzon, J., and Turlings, T.C.J., Recruitment of entomopathogenic nematodes by insect damaged maize roots, *Nature*, 2005, vol. 434, pp. 732–737.
  11. Aharoni, A., Giri, A.P., Deurlein, S., Griepink, F., de Kogel, W.J., Verstappen, F.W.A., Verhoeven, H.A., Jongsma, M.A., Schwab, W., and Bouwmeester, H.J., Terpenoid metabolism in wild-type and transgenic *Arabidopsis* plants, *Plant Cell*, 2003, vol. 15, pp. 2866–2884.
  12. Chen, F., Tholl, D., D'Auria, J.C., Farooq, A., Pichersky, E., and Gershenzon, J., Biosynthesis and emission of terpenoid volatiles from *Arabidopsis* flowers, *Plant Cell*, 2003, vol. 2, pp. 481–494.
  13. Aubourg, S., Lechary, A., and Bohlmann, J., Genomic analysis of the terpenoid synthase (AtTPS) gene family of *Arabidopsis thaliana*, *Mol. Genet. Genomics*, 2002, vol. 267, pp. 730–745.
  14. Tholl, D., Chen, F., Petri, J., Gershenzon, J., and Pichersky, E., Two sesquiterpene synthases are responsible for the complex mixture of sesquiterpenes emitted from *Arabidopsis* flowers, *Plant J.*, 2005, vol. 42, pp. 757–771.
  15. Aharoni, A., Jongsma, M.A., Kim, T.Y., Ri, M.B., Giri, A.P., Verstappen, F.W.A., Schwab, W., and Bouwmeester, H.J., Metabolic engineering of terpenoid biosynthesis in plants, *Phytochem. Rev.*, 2006, vol. 5, pp. 49–58.
  16. Huang, M., Abel, C., Sohrabi, R., Petri, J., Haupt, I., Cosimano, J., Gershenzon, J., and Tholl, D., Variation of herbivore-induced volatile terpenes among *Arabidopsis* ecotypes depends on allelic differences and subcellular targeting of two terpene synthases, TPS02 and TPS03, *Plant Physiol.*, 2010, vol. 153, pp. 1293–1310.
  17. Steeghs, M., Bais, H.P., de Gouw, J., Goldan, P., Kuster, W., Northway, M., Fall, R., and Vivanco, J.M., Proton-transfer-reaction mass spectrometry as a new tool for real time analysis of root-secreted volatile organic compounds in *Arabidopsis*, *Plant Physiol.*, 2004, vol. 135, pp. 47–58.
  18. Juenger, T.E., Sen, S., Bray, E., Stahl, E., Wayne, T., McKay, J., and Richards, J.H., Exploring genetic and expression differences between physiologically extreme ecotypes: comparative genomic hybridization and gene expression studies of Kas-1 and Tsu-1 accessions of *Arabidopsis thaliana*, *Plant Cell Environ.*, 2010, vol. 33, pp. 1268–1284.
  19. Kappers, I.F., Aharoni, A., van Herpen, T.W.J.M., Luckenhoff, L.L.P., Dicke, M., and Bouwmeester, H.J., Genetic engineering of terpenoid metabolism attracts bodyguards to *Arabidopsis*, *Science*, 2005, vol. 309, pp. 2070–2072.
  20. Gibeau, D.M., Hulett, J., Cramer, G.R., and Seemann, J.R., Maximal biomass of *Arabidopsis thaliana* using a simple, low-maintenance hydroponic method and favorable environmental conditions, *Plant Physiol.*, 1997, vol. 115, pp. 317–319.
  21. Genty, B., Briantais, J.M., and Baker, N.R., The relationship between the quantum yield of photosynthetic electron transport and quenching of chlorophyll fluorescence, *Biochim. Biophys. Acta*, 1989, vol. 990, pp. 87–92.
  22. Blanch, J.S., Sampedro, L., Llusà, J., Moreira, X., Zas, R., and Peñuelas, J., Effects of phosphorus availability and genetic variation of leaf terpene content and emission rate in *Pinus pinaster* seedlings susceptible and resistant to the pine weevil, *Hylobius abietis*, *J. Chem. Ecol.*, 2012, vol. 14, pp. 66–72.
  23. Van Poecke, R.M.P., Posthumus, M.A., and Dicke, M., Herbivore-induced volatile production by *Arabidopsis thaliana* leads to attraction of the parasitoid *Cotesia rubecula*: chemical, behavioral, and gene-expression analysis, *J. Chem. Ecol.*, 2001, vol. 27, pp. 1911–1928.
  24. Nagegowda, D.A., Plant volatile terpenoid metabolism: biosynthetic genes, transcriptional regulation and subcellular compartmentation, *FEBS Lett.*, 2010, vol. 384, pp. 2965–2973.
  25. Meir, S., Reuveni, Y., Rosenberger, I., Davidson, H., and Philosophadas, S., Improvement of the postharvest keeping quality of cut flowers and cuttings by application of water-soluble antioxidants, *ISHS Acta Hort.*, 1994, vol. 368, pp. 355–364.
  26. Hedtke, B., Meixner, M., Gillandt, S., Richter, E., Borner, T., and Weihe, A., Green fluorescent protein as a marker to investigate targeting of organellar RNA polymerases of higher plants *in vivo*, *Plant J.*, 1999, vol. 17, pp. 557–561.
  27. Beemster, G.T.S., de Vusser, K., de Tavernier, E., de Bock, K., and Inzé, D., Variation in growth rate between *Arabidopsis* ecotypes is correlated with cell division and A-type cyclin-dependent kinase activity, *Plant Physiol.*, 2002, vol. 129, pp. 854–864.
  28. Oxborough, K. and Baker, N.R., Resolving chlorophyll *a* fluorescence images of photosynthetic efficiency into photochemical and non-photochemical components – calculation of qP and  $F_v'/F_m'$  without measuring  $F_0'$ , *Photosynth. Res.*, 1997, vol. 54, pp. 135–142.
  29. van Dam, N.M. and van der Meijden, E., A role for metabolomics in plant ecology, in *Biology of Plant Metabolomics*, Hall, R.D., Ed., Chichester, UK: Wiley, 2011, pp. 87–107.
  30. Basyuni, M., Baba, S., Inafuku, M., Iwasaki, H., Kinjo, K., and Oku, H., Expression of terpenoid synthase mRNA and terpenoid contents in salt stressed mangrove, *J. Plant Res.*, 2009, vol. 166, pp. 1786–1800.