

Rapid report

Isoprene emission rates under elevated CO₂ and O₃ in two field-grown aspen clones differing in their sensitivity to O₃

Author for correspondence:

Carlo Calfapietra

Tel: +39 06 90672530

Fax: +39 06 9064492

Email: carlo.calfapietra@ibaf.cnr.it

Received: 27 February 2008

Accepted: 20 April 2008

Carlo Calfapietra^{1,2}, Giuseppe Scarascia Mugnozza^{1,2}, David F. Karnosky³, Francesco Loreto¹ and Thomas D. Sharkey⁴

¹CNR- Istituto di Biologia Agroambientale e Forestale, Via Salaria Km. 29.300 00016 Monterotondo Scalo (Roma), Italy; ²University of Tuscia, Department of Forest Environment and Resources (DISAFRI), Via S.Camillo de Lellis snc, 01100 Viterbo, Italy; ³School of Forest Resources and Environmental Science, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA; ⁴Michigan State University, 410 Biochemistry Building, East Lansing, MI 48824, USA

Summary

Key words: carotenoids, dimethylallyl diphosphate (DMADP), elevated CO₂, free air CO₂ enrichment (FACE), isoprene, ozone (O₃) uptake, *Populus*.

- Isoprene is the most important nonmethane hydrocarbon emitted by plants. The role of isoprene in the plant is not entirely understood but there is evidence that it might have a protective role against different oxidative stresses originating from heat shock and/or exposure to ozone (O₃). Thus, plants under stress conditions might benefit by constitutively high or by higher stress-induced isoprene emission rates.
- In this study, measurements are presented of isoprene emission from aspen (*Populus tremuloides*) trees grown in the field for several years under elevated CO₂ and O₃. Two aspen clones were investigated: the O₃-tolerant 271 and the O₃-sensitive 42E.
- Isoprene emission decreased significantly both under elevated CO₂ and under elevated O₃ in the O₃-sensitive clone, but only slightly in the O₃-tolerant clone.
- This study demonstrates that long-term-adapted plants are not able to respond to O₃ stress by increasing their isoprene emission rates. However, O₃-tolerant clones have the capacity to maintain higher amounts of isoprene emission. It is suggested that tolerance to O₃ is explained by a combination of different factors; while the reduction of O₃ uptake is likely to be the most important, the capacity to maintain higher amounts of isoprene is an important factor in strengthening this character.

New Phytologist (2008) **179**: 55–61

© The Authors (2008). Journal compilation © *New Phytologist* (2008)

doi: 10.1111/j.1469-8137.2008.02493.x

Introduction

Isoprene is the most abundant hydrocarbon emitted by vegetation, and this emission may have large consequences for the chemistry of the atmosphere (Guenther *et al.*, 1995; Wang & Shallcross, 2000; Karl *et al.*, 2004; Yokouchi & Ambe, 2007). The genus *Populus* includes some of the highest

isoprene-emitting species (Lenz *et al.*, 2001). *Populus* species are widely used in short-rotation plantations that are becoming common in agroforestry (FAO, 2005), thus contributing heavily to the global isoprene pool released into the atmosphere. Global change is expected to influence heavily isoprene emission from plants. Global warming is expected to stimulate isoprene emission, but the effects of rising

atmospheric CO₂ and tropospheric ozone (O₃) episodes remain uncertain, in particular because of the indirect and feedback effects that might occur at the ecosystem level (Arneeth *et al.*, 2008). A series of experiments showed a decrease of basal isoprene emission under elevated CO₂ (Rosenstiel *et al.*, 2003; Possell *et al.*, 2004; Scholefield *et al.*, 2004). Using different models, it was estimated that the positive effect of warming on global isoprene emission might be balanced by the negative effect of rising CO₂ concentration (Arneeth *et al.*, 2008), with crucial repercussions on tropospheric ozone and aerosols (Liao *et al.*, 2006). While we are aware of the important role of isoprene on the formation of O₃, very little is known about the effect of elevated tropospheric O₃ on the emission of isoprene or volatile organic compounds. In a few laboratory studies it was observed that isoprene emission might increase following exposure to a high level of O₃ (Velikova *et al.*, 2005a), although the effect seems to be modulated by the position and the age of the leaf (Fares *et al.*, 2006). Different responses to O₃ in terms of monoterpene emission rates were observed in various Mediterranean species (Llusià *et al.*, 2002). The role of isoprene in protection against oxidative stress deriving from O₃ exposure has been more thoroughly investigated (Loreto & Velikova, 2001; Velikova *et al.*, 2005b). In particular it has been shown that when isoprene is provided to nonemitting plants, O₃ damage is considerably reduced, whereas O₃ damage is induced when isoprene synthesis is inhibited in isoprene emitters (Loreto & Fares, 2007). Lerda (2007) suggested that increasing the concentration of atmospheric O₃ will favour isoprenoid-emitting species over nonemitting species because of the protective role of isoprenoids on O₃ stress.

We measured isoprene emission in an O₃-tolerant clone (271) and an O₃-sensitive clone (42E) of aspen grown for several years under elevated O₃ and elevated CO₂, alone or in combination, at the AspenFACE facility. In a previous manuscript we showed that isoprene synthase (ISPS), the enzyme responsible for isoprene synthesis, was inhibited at both transcriptional and translational levels by treatment with O₃. In this study we present data deriving from a large campaign carried out in early summer and aimed to establish whether the different O₃ sensitivity of clones is related to O₃ uptake and isoprene emission.

Materials and Methods

Site description

The experiment was carried out at the AspenFACE facility located in Rhineland (Northern Wisconsin, USA). The AspenFACE experiment started in 1998 when 12 experimental plots were planted that underwent four different treatments, as follows: ambient CO₂ and O₃ (control); elevated CO₂ and ambient O₃ (CO₂); ambient CO₂ and elevated O₃ (O₃); and elevated CO₂ and elevated O₃ (CO₂ + O₃). The target for

elevated CO₂ at the AspenFACE is 560 ppm and for elevated O₃ is 1.5× ambient concentration. Details on the layout of the plots and of the fumigation performances are given in the AspenFACE website (<http://aspenface.mtu.edu>). In our study, samples were collected only within the sectors occupied by the trembling aspen (*Populus tremuloides* Michx.) clones. Two clones were investigated, namely 271 (O₃ tolerant) and 42E (O₃ sensitive) (Isebrands *et al.*, 2001; Karnosky *et al.*, 2003). These two clones exhibited the most contrasting responses to O₃ in a previous campaign focusing on the isoprene synthase gene and isoprene synthase protein (Calfapietra *et al.*, 2007).

Leaf gas-exchange measurements

An intensive campaign was carried out from 26 June to 12 July 2006 to measure leaf gas exchange in six sun-exposed leaves from the upper canopy of each clone in each plot. Measurements were carried out on sunny days and from 10:00 to 16:00 h every day in order to measure parameters under homogeneous environmental and physiological conditions.

A LI-COR 6400 (LI-COR Inc., Lincoln, NE, USA) infrared gas analyzer was used for measurements of photosynthesis, stomatal conductance to water vapor diffusion (g_s) and emission of isoprene under environmental conditions that were previously standardized (basal emission, Guenther *et al.*, 1991). Leaf temperature was set at 30°C and photosynthetic photon flux density (PPFD) at 1000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Measurements were carried out at the O₃ and CO₂ concentrations at which plants were growing. Peak hourly O₃ concentrations during the campaign were 46 ppb and 65 ppb in the ambient and elevated O₃ plots, respectively. To avoid CO₂ oscillations during measurements, a fixed CO₂ concentration of 560 and 370 ppm, simulating growth conditions in the different plots, was set with the LI-COR 6400 equipment. The outlet of the LI-COR 6400 cuvette was connected to a Fast Isoprene Sensor (Hills Scientific, Boulder, CO, USA) for online measurements of isoprene emission, as described by Hanson & Sharkey (2001).

Ozone uptake was calculated by multiplying data of O₃ concentration and stomatal conductance to O₃ during leaf gas-exchange measurements (Emberson *et al.*, 2000). Stomatal conductance to water vapor diffusion (g_s) was converted to O₃ conductance by dividing the g_s value by the coefficient of molecular diffusivity of O₃ in water vapor (1.68), and assuming that the concentration of O₃ inside the intracellular spaces of the leaf is approximately zero (Laisk *et al.*, 1989).

After measurements were taken, leaves were immediately frozen in dry ice and then stored at -80°C until used in biochemical assays.

Biochemical assays

The assay for dimethylallyl diphosphate (DMADP) was carried out on tissue samples previously ground and subjected

Table 1 Values of leaf gas exchange, isoprene emission, and dimethylallyl diphosphate (DMADP) and carotenoid contents of the leaves in the aspen (*Populus tremuloides*) clones 271 (O_3 -tolerant) and 42E (O_3 -sensitive) in the four treatments

	Control		CO_2		O_3		$CO_2 + O_3$		<i>P</i> values		
	271	42E	271	42E	271	42E	271	42E	CO_2	O_3	Clone
Assimilation ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	12.9 ^{ab} (0.3)	13.7 ^{ab} (0.3)	17.4 ^{cd} (0.7)	20.2 ^d (0.5)	11.7 ^b (1.1)	12.7 ^{ab} (1.6)	15.4 ^{ac} (1.4)	15.1 ^{ac} (1.8)	0.000	0.010	0.184
g_s ($\text{mol m}^{-2} \text{s}^{-1}$)	0.20 ^{ab} (0.01)	0.24 ^{ab} (0.02)	0.15 ^b (0.01)	0.26 ^{ab} (0.03)	0.19 ^{ab} (0.04)	0.28 ^a (0.08)	0.16 ^b (0.03)	0.20 ^{ab} (0.05)	0.231	0.878	0.027
C_i (ppm)	207 ^a (5)	214 ^a (8)	292 ^b (12)	354 ^b (15)	203 ^a (23)	221 ^a (32)	299 ^b (27)	335 ^b (28)	0.000	0.872	0.054
Ozone uptake ($\text{nmol m}^{-2} \text{s}^{-1}$)	5.2 ^a (0.3)	6.3 ^a (0.6)	3.5 ^a (0.19)	6.1 ^a (0.6)	7.9 ^{ab} (2.5)	11.7 ^b (4.4)	6.3 ^{ab} (1.7)	8.0 ^{ab} (2.2)	0.233	0.044	0.137
Isoprene emission ($\text{nmol m}^{-2} \text{s}^{-1}$)	47.1 ^a (0.7)	44.5 ^a (2.6)	41.6 ^{ab} (3.6)	34.4 ^c (3.4)	40.4 ^{abc} (3.1)	35.5 ^{bc} (0.7)	36.2 ^{bc} (1.5)	23.9 ^d (1.3)	0.000	0.000	0.001
DMADP (ng mg^{-1} FW)	2.6 ^a (0.2)	2.5 ^a (0.2)	1.8 ^b (0.2)	1.8 ^b (0.2)	1.9 ^b (0.1)	2.0 ^b (0.1)	1.8 ^b (0.1)	2.1 ^{ab} (0.1)	0.003	0.173	0.561
Carotenoids (mg g^{-1} FW)	0.73 ^a (0.03)	0.61 ^a (0.08)	0.69 ^a (0.06)	0.56 ^a (0.03)	0.69 ^a (0.10)	0.53 ^a (0.03)	0.70 ^a (0.01)	0.56 ^a (0.04)	0.806	0.805	0.043

The effect of CO_2 , O_3 and clone is indicated by the *P* values in the last three columns at the right of the table (a significant effect is shown in bold). The interactions between these factors are never significant and therefore are not reported. Letters in superscript indicate differences identified from the *post hoc* multiple comparison using the Fischer's test. For each parameter, values with the same letter are not significantly different. Values are means (SE) ($n =$ three plots). FW, fresh weight.

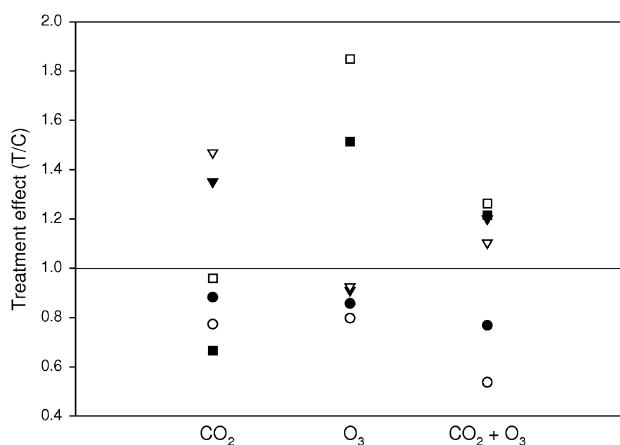


Fig. 1 Treatment effect calculated as treated (T) over control (C) for O_3 uptake (squares), assimilation rates (triangles) and isoprene emission (circles) by aspen (*Populus tremuloides*) trees. Closed symbols, O_3 -tolerant clone 271; open symbols, O_3 -sensitive clone 42E.

to acid hydrolysis with 1 M H_3PO_4 at 60°C for 30 min. The powdered leaf samples were incubated with 500 μl of H_2O and 500 μl of H_3PO_4 in 4-ml vials sealed with inert caps. Pure N_2 was continuously flushed in the vials at a flux of 100 ml min^{-1} . The air exiting the vial was injected directly into the Proton Transfer Reaction-Mass Spectrometer (PTR-MS; Ionicon, Innsbruck, Austria). The amount of DMADP was calculated after measuring the amount of isoprene evolved by the hydrolysis (protonated m/z 69), as indicated by Fisher *et al.* (2001) and Brüggeman & Schnitzler (2002).

Standard DMADP (1 mg ml^{-1} ; Sigma-Aldrich, St Louis, MO, USA) was used at amounts of 2.5, 5, 10 and 20 μl for calibrations of the PTR-MS.

Total carotenoids were extracted in 96% ethanol and detected spectrophotometrically, as described in Calfapietra *et al.* (2003).

Statistics

Analysis of variance (ANOVA) was carried out to determine the effects of elevated CO_2 , elevated O_3 and clone. The SYSTAT 11 software (Systat Software Inc., Richmond, CA, USA) general linear models procedure was used. Thereafter, the significance within each combination of clone, CO_2 and O_3 treatments was calculated using Fischer's multiple comparison procedure. Differences between means were considered significant at a *P* value of < 0.05.

Results

Plants grown at elevated CO_2 had higher photosynthesis but lower isoprene emission than controls grown at ambient CO_2 . The CO_2 effect on photosynthesis was significant for both clones, whereas the effect on isoprene was only significant for the O_3 -sensitive clone 42E (Fig. 1, Table 1). Under conditions of elevated CO_2 , DMADP concentrations dropped considerably in both clones compared with the control, whereas the amount of carotenoids was only slightly affected.

Stomatal conductance to water vapor diffusion (g_s) and O_3 uptake were not significantly affected by elevated CO_2 , although a decrease was observed in clone 271 (Fig. 1, Table 1).

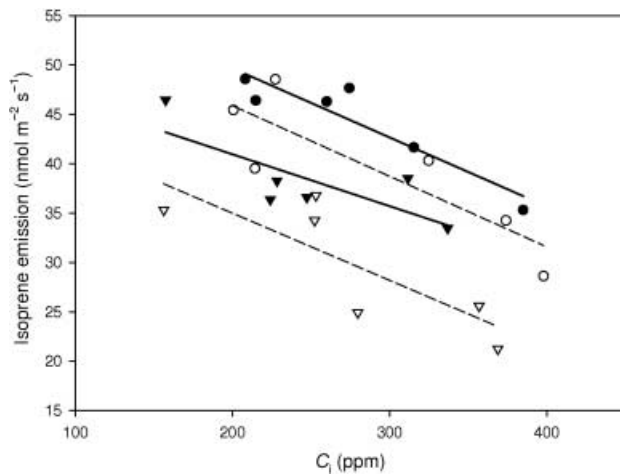


Fig. 2 Relationship between intercellular CO_2 concentration (C_i) and isoprene emission rates in aspen (*Populus tremuloides*) O_3 -tolerant clone 271 (circles) and in the O_3 -sensitive clone 42E (triangles) under ambient (closed symbols) or elevated (open symbols) O_3 . Each symbol represents the value of one plot. R^2 values range from 0.60 and 0.85 and P values from 0.04 to 0.008.

Elevated O_3 induced a drop in both photosynthesis and isoprene emission, the latter being more affected. The DMADP concentration also decreased under conditions of elevated O_3 , but to a lesser extent than under elevated CO_2 . Ozone uptake was largely increased under elevated O_3 , especially in clone 42E which also showed a slight O_3 -induced increment of g_s .

When elevated O_3 was combined with elevated CO_2 , the stimulating effect of CO_2 on photosynthesis was almost completely suppressed, especially in the case of clone 42E. The combination of elevated CO_2 and O_3 induced a large

decrease in the isoprene emission rate, especially in clone 42E. The concentrations of DMADP were also reduced in comparison with the control, whereas the amount of carotenoids did not change significantly with treatments, but were lower in clone 42E than in clone 271.

Isoprene emission rates decreased linearly with the increase of intercellular CO_2 concentration (C_i) for both clones and in both O_3 treatments. At a given value of C_i , isoprene emission was lower in elevated O_3 than in ambient O_3 , and was also lower in clone 42E than in clone 271 (Fig. 2).

Differences between clones became more evident when different isoprene emission rates and O_3 uptake were compared. Ozone uptake was higher in clone 42E than in clone 271, whereas isoprene emission was higher in clone 271 than in clone 42E at all isoprene emission levels (Fig. 3). Interestingly, differences in O_3 uptake between clones increased with the increase of O_3 uptake (slope significantly different from 1, intercept not significantly different from 0). Differences in isoprene emission rates between clones were larger at low rates (corresponding to values under elevated O_3) than at higher rates, as shown by the intercept being significantly different from 0.

Discussion

Both elevated CO_2 and O_3 induced a decrease in isoprene emission rates in closed canopy free air CO_2 enrichment (FACE)-grown trees. However, the effect of elevated CO_2 was significant for the O_3 -sensitive clone but not for the O_3 -tolerant clone. A reduction of isoprene emission under elevated CO_2 was previously found in experiments in closed environments (Rosenstiel *et al.*, 2003; Possell *et al.*, 2004), in natural springs

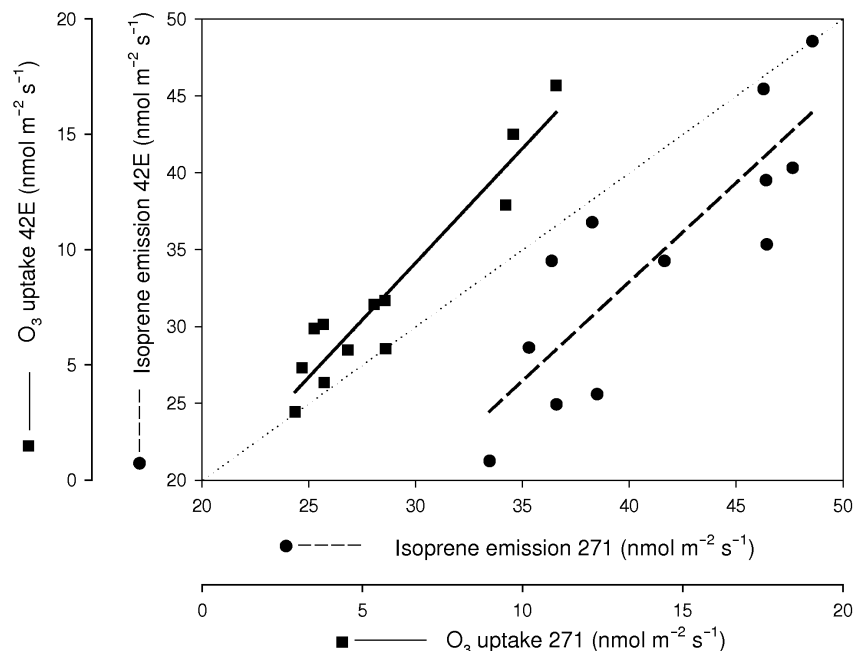


Fig. 3 Comparison between the aspen (*Populus tremuloides*) O_3 -tolerant clone 271 and the O_3 -sensitive clone 42E in O_3 uptake (squares) and isoprene emission (circles). Each point represents the values of the two clones in each plot. The dotted line represents the 1:1 line. Fit line for O_3 uptake has $R^2 = 0.91$ and $P < 0.0001$, whereas for isoprene emission $R^2 = 0.72$ and $P < 0.001$.

(Scholefield *et al.*, 2004) and at different FACE sites (Monson *et al.*, 2007), but no significant effect of elevated CO₂ on isoprene emission was observed for *Populus alba* in the POP-EUROFACE experiment (Loreto *et al.*, 2007). A decrease of isoprene emission with increasing C_i has been measured previously (Loreto *et al.*, 2007; Monson *et al.*, 2007). Here we show that this relationship exists in different clones and also under conditions of elevated O₃. This confirms the observed CO₂ sensitivity of isoprene synthesis, probably because the cytosolic source of carbon for isoprene is more efficiently competed for by respiratory processes under high CO₂ (Rosenstiel *et al.*, 2003; Loreto *et al.*, 2007). For each value of C_i, isoprene emission was higher in the O₃-tolerant clone than in the O₃-sensitive clone, and higher under ambient O₃ than under elevated O₃.

The high C_i value measured in clone 42E was associated with a high g_s value, which is typical of this clone (Darbah, 2007). The effect of clone on C_i was not fully significant ($P = 0.054$) because of the high variability of measurements. However, O₃ uptake was higher in clone 42E than in clone 271 in all plots. In addition, the g_s value of clone 42E plants was not reduced under elevated O₃, whereas this is usually the case in other aspen clones (Karnosky *et al.*, 2003). High C_i might be also the consequence of inefficient photosynthesis (Evans & Loreto, 2000). However, photosynthesis in the O₃-sensitive and O₃-tolerant clones was similar within each treatment and does not explain the differences observed of C_i. Variability in C_i was quite high and differences were strong both among clones and CO₂ treatments, where values of the C_i/C_a ratio (where C_a is the ambient CO₂ concentration) were found to be lower under ambient CO₂ than under elevated CO₂. This might be attributed to the onset of a hot and dry period that reached a peak later in the season and that affected trees under ambient CO₂ to a major extent, mainly as a result of generally higher stomatal conductance.

Clone 42E was more sensitive to O₃ than clone 271 in several experiments, showing decreased photosynthesis, decreased growth rates and increased visible symptoms (Isebrands *et al.*, 2001; Wustman *et al.*, 2001; Karnosky *et al.*, 2003). In this study, however, the expected decline of photosynthesis under O₃ was not observed. This may be attributed to the fact that the campaign was carried out quite early in the season. Noormets *et al.* (2001) showed that the negative effect of O₃ becomes evident only in leaves with a high leaf plastochrone index (i.e. on older leaves undergoing a long exposure to O₃). This finding is particularly important because it shows that the effect of O₃ on isoprene synthesis is greater, or occurs earlier, than that on assimilation. Unfortunately, data on specific leaf area are not available for all clones and for all treatments and therefore it is not possible to assess whether variations observed on a leaf area basis for these clones would have been different on a leaf mass basis.

High O₃ uptake is probably the main reason why clone 42E is very sensitive to O₃ (Karnosky *et al.*, 2003). However,

isoprene emission may also play a role in O₃ sensitivity. It has been demonstrated that plants emitting higher amounts of isoprenoids are more protected against oxidative stress, probably because isoprenoids can increase the cohesion between cellular structures and can scavenge O₃ inside leaves (Loreto & Velikova, 2001; Loreto & Fares, 2007). This second hypothesis might lead to the idea that decreased isoprene emission rates under elevated O₃ are a result of the fact that isoprene is reacting with O₃ before exiting the leaf. However, it has been explained that the lifetime of isoprene in our measurement conditions is c. 8 h (Calfapietra *et al.*, 2007) and therefore the contribution to O₃ uptake as a result of scavenging by isoprenoids is important for monoterpenes but negligible for isoprene (Fares *et al.*, 2008).

Isoprene emission was considerably lower in the O₃-sensitive clone, particularly when the emission was reduced by elevated O₃. Therefore, we suggest that the capacity to maintain higher levels of isoprene emission contributes to the O₃ tolerance of clone 271.

Moreover, carotenoid content was higher in clone 271 leaves than in clone 42E leaves. Carotenoids are formed through the same biochemical pathway as isoprene (Laule *et al.*, 2003) and are able to quench singlet oxygen and other reactive oxygen species (Asada, 2006). The finding that both isoprene and carotenoids are higher in clone 271 suggests that resistance to O₃ is related to the activation of the entire metabolic pathway of isoprene formation, including both volatile and nonvolatile compounds with antioxidant action. However, our experiments do not rule out that isoprene emission and the amount of carotenoids remain higher in O₃-tolerant lines because of independent O₃ tolerance mechanisms that preserve isoprene emission capacity and carotenoids amount independently.

In a previous paper (Calfapietra *et al.*, 2007) we showed that the level of isoprene synthase gene expression and amount of isoprene synthase protein were reduced in aspen clones grown under elevated O₃, especially in sensitive clones. This report, on the other hand, shows that DMADP, the substrate for isoprene synthesis, decreased significantly only under elevated CO₂. Therefore, the decline of isoprene emission observed when elevated CO₂ and elevated O₃ co-occur may be exacerbated by a combination of substrate limitation and enzyme limitation. Moreover the amount of DMADP was very similar between clones, suggesting that differences in isoprene emission between clones might be caused more by differences in the enzyme amount or activity rather than by the substrate concentration.

Acknowledgements

This research was supported by a *Marie Curie International Fellowship* within the 6th European Community Framework Programme ('GLOBALVOC', contract MOIF-CT-2005-007692) and by the Italy-USA Bilateral Programme on Climate Change of the Italian Ministry of Environment. The

AspenFACE experiment is funded by the Office of Science (BER), US Department of Energy, the National Science Foundation, the USFS Global Change Program, Michigan Technological University, and the USFS North Central Research Station. The authors wish to thank Tanja Falbel, Amy Wiberley, Angela Elwell and Isabel Nogues for help during the field and laboratory activities and Prof. Rich Lindroth for providing useful equipment during the field campaign.

References

- Arnell A, Schurgers G, Hickler T, Miller PA. 2008. Effects of species composition, land surface cover, CO₂ concentration and climate on isoprene emissions from European Forests. *Plant Biology* 10: 150–162.
- Asada K. 2006. Production and scavenging of reactive oxygen species in chloroplasts and their functions. *Plant Physiology* 141: 391–396.
- Brüggeman N, Schnitzler JP. 2002. Diurnal variation of dimethylallyl diphosphate concentrations in oak (*Quercus robur* leaves). *Physiologia Plantarum* 115: 190–196.
- Calfapietra C, De Angelis P, Kuzminsky E, Scarascia-Mugnozza GE. 2003. Impact of elevated CO₂ concentration on leaf development in *Populus nigra* in a 'Free Air Carbon Dioxide Enrichment' experiment. In: De Angelis P, Macuz A, Bucci G, Scarascia-Mugnozza G, eds. *Alberi e Foreste per il Nuovo Millennio. Proceedings of the 3rd National Congress of SISEF*. Viterbo, Italy: SISEF, 357–362.
- Calfapietra C, Wiberley AE, Falbel TG, Linskey AR, Scarascia Mugnozza G, Karnosky DF, Loreto F, Sharkey TD. 2007. Isoprene synthase expression and protein levels are reduced under elevated O₃ but not under elevated CO₂ (FACE) in field-grown aspen trees. *Plant, Cell & Environment* 30: 654–661.
- Darbah JNT. 2007. Impacts of elevated atmospheric CO₂ and/or O₃ on carbon gain and reproductive capacity in northern forest ecosystems. PhD thesis, Michigan Technological University, Houghton, MI, USA.
- Emmerson LD, Ashmore MR, Cambridge HM, Simpson D, Tuovinen J. 2000. Modelling stomatal ozone flux across Europe. *Environmental Pollution* 109: 403–413.
- Evans JR, Loreto F. 2000. Acquisition and diffusion of CO₂ in higher plant leaves. In: Leegood RC, Sharkey TD, Von Caemmerer S, eds. *Photosynthesis physiology and metabolism*. Dordrecht, the Netherlands: Kluwer Academic Publisher, 321–351.
- FAO. 2005. *Report of the 22nd session of the International Poplar Commission and 42nd session of its Executive Committee*. Santiago, Chile: FAO.
- Fares S, Barta C, Brillì F, Centritto M, Ederli L, Ferranti F, Pasqualini S, Reale L, Tricoli D, Loreto F. 2006. Impact of high ozone on isoprene emission, photosynthesis and hysteresis of developing *Populus alba* leaves directly or indirectly exposed to the pollutant. *Physiologia Plantarum* 128: 456–465.
- Fares S, Loreto F, Kleist E, Wildt J. 2008. Stomatal uptake and stomatal deposition of ozone in isoprene and monoterpene emitting plants. *Plant Biology* 10: 44–54.
- Fisher AJ, Rosenstiel TN, Shirk MC, Fall R. 2001. Nonradioactive assay for cellular dimethylallyl diphosphate. *Analytical Biochemistry* 292: 272–279.
- Guenther A, Hewitt CN, Eriksson D, Fall R, Geron C, Graedel T, Harley P, Klinger L, Lerdau M, McKay WA *et al.* 1995. A global model of natural volatile organic compound emissions. *Journal of Geophysical Research–Atmospheres* 100: 8873–8892.
- Guenther AB, Monson RK, Fall R. 1991. Isoprene and monoterpene emission rate variability: observations with eucalyptus and emission rate algorithm development. *Journal of Geophysical Research* 96: 799–808.
- Hanson DT, Sharkey TD. 2001. Rate of acclimation of the capacity for isoprene emission in response to light and temperature. *Plant, Cell & Environment* 24: 937–946.
- Isebrands JG, McDonald EP, Kruger E, Hendry G, Pregitzer K, Sober J, Karnosky DF. 2001. Growth responses of *Populus tremuloides* clones to interacting carbon dioxide and tropospheric ozone. *Environmental Pollution* 115: 359–371.
- Karl T, Potosnak M, Guenther A, Clark D, Walker J, Herrick JD, Geron C. 2004. Exchange processes of volatile organic compounds above a tropical rain forest: implications for modeling tropospheric chemistry above dense vegetation. *Journal of Geophysical Research–Atmospheres* 109 (D18): doi: 10.1029/2004JD004738.
- Karnosky DF, Zak DR, Pregitzer KS, Awmack CS, Bockheim JG, Dickson RE, Hendrey GR, Host GE, King JS, Kopper BJ *et al.* 2003. Tropospheric O₃ moderates responses of temperate hardwood forests to elevated CO₂: a synthesis of molecular to ecosystem results from the Aspen FACE project. *Functional Ecology* 17: 289–304.
- Laisk A, Kull O, Moldau H. 1989. Ozone concentration in leaf intercellular air spaces is close to zero. *Plant Physiology* 90: 1163–1167.
- Laule O, Furrholz A, Chang HS, Zhu T, Wang X, Heifetz PB, Grisse W, Lange M. 2003. Crosstalk between cytosolic and plastidial pathways of isoprenoid biosynthesis in *Arabidopsis thaliana*. *Proceedings of the National Academy of Sciences, USA* 100: 6866–6871.
- Lenz R, Köble R, Seufert G. 2001. *Species-based mapping of biogenic emissions in Europe: a case study Italy*. Proceedings of the 8th European Symposium of the physico-chemical behaviour of the photochemical pollutants. Turin, Italy.
- Lerdau M. 2007. A positive feedback with negative consequences. *Science* 316: 212–213.
- Liao H, Chen WT, Seinfeld JH. 2006. Role of climate change in global predictions of future tropospheric ozone and aerosols. *Journal of Geophysical Research–Atmospheres* 111 (D12): 12304, doi: 10.1029/2005JD006852.
- Llusà J, Peñuelas J, Gimeno BS. 2002. Seasonal and species-specific response of VOC emissions by Mediterranean woody plant to elevated ozone concentrations. *Atmospheric Environment* 36: 3931–3938.
- Loreto F, Centritto M, Barta C, Calfapietra C, Fares S, Monson R. 2007. The relationship between isoprene emission rate and dark respiration rate in white poplar (*Populus alba* L.) leaves. *Plant, Cell & Environment* 30: 662–669.
- Loreto F, Fares S. 2007. Is ozone flux inside leaves only a damage indicator? Clues from volatile isoprenoid studies. *Plant Physiology* 143: 1096–1100.
- Loreto F, Velikova V. 2001. Isoprene produced by leaves protects the photosynthetic apparatus against ozone damage, quenches ozone products, and reduces lipid peroxidation of cellular membranes. *Plant Physiology* 127: 1781–1787.
- Monson RK, Trahan N, Rosenstiel TN, Veres P, Moore D, Wilkinson M, Norby RJ, Volder A, Tjoelker MG, Briske DD *et al.* 2007. Isoprene emission from terrestrial ecosystems in response to global change: minding the gap between models and observations. *Philosophical Transactions of the Royal Society A* 365: 1677–1695.
- Noormets A, Sober A, Pell EJ, Dickson RE, Podila GK, Sober J, Isebrands JG, Karnosky DF. 2001. Stomatal and nonstomatal limitation to photosynthesis in two trembling aspen (*Populus tremuloides* Michx.) clones exposed to elevated CO₂ and/or O₃. *Plant, Cell & Environment* 24: 327–336.
- Possell M, Heath J, Hewitt CN, Ayres E, Kerstiens G. 2004. Interactive effects of elevated CO₂ and soil fertility on isoprene emissions from *Quercus robur*. *Global Change Biology* 10: 1835–1843.
- Rosenstiel TN, Potosnak MJ, Griffin KL, Fall R, Monson RK. 2003. Increased CO₂ uncouples growth from isoprene emission in an agriforest ecosystem. *Nature* 421: 256–259.
- Scholefield PA, Doick KJ, Herbert BMJ, Hewitt CNS, Schnitzler J-P, Pinelli P, Loreto F. 2004. Impact of rising CO₂ on emission of volatile organic compounds: isoprene emission from *Phragmites australis* growing at elevated CO₂ in a natural carbon dioxide spring. *Plant, Cell & Environment* 27: 393–401.

Velikova V, Pinelli P, Pasqualini S, Reale L, Ferranti F, Loreto F. 2005b. Isoprene decreases the concentration of nitric oxide in leaves exposed to elevated ozone. *New Phytologist* 166: 419–426.

Velikova V, Tsonev T, Pinelli P, Alessio GA, Loreto F. 2005a. Localized ozone fumigation system for studying ozone effects on photosynthesis, respiration, electron transport rate and isoprene emission in field-grown Mediterranean oak species. *Tree Physiology* 25: 1523–1532.

Wang K-Y, Shallcross DE. 2000. Modelling terrestrial biogenic isoprene

fluxes and their potential impact on global chemical species using a coupled LSM-CTM model. *Atmospheric Environment* 34: 2909–2925.

Wustman BA, Oksanen E, Karnosky DF, Sober J, Isebrands JG, Hendrey GR, Pregitzer KS, Podila GK. 2001. Effects of elevated CO₂ and O₃ on aspen clones varying in O₃ sensitivity: can CO₂ ameliorate the harmful effects of O₃? *Environmental Pollution* 115: 473–481.

Yokouchi Y, Ambe Y. 2007. Aerosols formed from the chemical reaction of monoterpenes and ozone. *Atmospheric Environment* 41 (Suppl. 1): 192–197.



About *New Phytologist*

- *New Phytologist* is owned by a non-profit-making **charitable trust** dedicated to the promotion of plant science, facilitating projects from symposia to open access for our Tansley reviews. Complete information is available at www.newphytologist.org.
- Regular papers, Letters, Research reviews, Rapid reports and both Modelling/Theory and Methods papers are encouraged. We are committed to rapid processing, from online submission through to publication 'as-ready' via *OnlineEarly* – our average submission to decision time is just 29 days. Online-only colour is **free**, and essential print colour costs will be met if necessary. We also provide 25 offprints as well as a PDF for each article.
- For online summaries and ToC alerts, go to the website and click on 'Journal online'. You can take out a **personal subscription** to the journal for a fraction of the institutional price. Rates start at £135 in Europe/\$251 in the USA & Canada for the online edition (click on 'Subscribe' at the website).
- If you have any questions, do get in touch with Central Office (newphytol@lancaster.ac.uk; tel +44 1524 594691) or, for a local contact in North America, the US Office (newphytol@ornl.gov; tel +1 865 576 5261).