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Enhanced ethylene production by primary roots of Zea mays L. in response to sub-ambient partial pressures of oxygen

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ABSTRACT
Ethylene production by primary roots of 72-h-old intact seedlings of Zea mays L. cv. LG11 was studied under ambient and sub-ambient oxygen partial pressures (pO2) using a gas flow-through system linked to a photoacoustic laser detector. Despite precautions to minimize physical perturbation to seedlings while setting-up, ethylene production in air was faster during the first 6h than later, in association with a small temporary swelling of the roots. When roots were switched from air (20.8 kPa O2) to 3 or 5 kPa O2 after 6h, ethylene production increased within 2-3h. When the roots were returned to air 16h later, ethylene production decreased within 2-3h. The presence of 10kPa CO2 did not interfere with the effect of 3kPa O2. Transferring roots from air to 12.5 kPa did not change ethylene production, while a reduction to 1 kPa O2 induced a small increase. The extra ethylene formed in 3 and 5 kPa O2 was associated with plagiotropism, swelling, root hair production, and after 72h, increased amounts of intercellular space (aerenchyma) in the root cortex. Root extension was also slowed down, but the pattern of response to oxygen shortage did not always match that of ethylene production. On return to air, subsequent growth patterns became normal within a few hours. In the complete absence of oxygen, no ethylene production was detected, even when anaerobic roots were returned to air after 16h.

Key-words: Zea mays L.; roots; flooding; environmental stress; ethylene; oxygen; carbon dioxide; aerenchyma; photoacoustic laser detector.

INTRODUCTION
Soil waterlogging significantly reduces the yield of most arable crops and pastures worldwide. Water itself is not toxic, but in excess, it asphyxiates roots by displacing soil oxygen and by impeding gaseous exchange between plant roots, the rhizosphere and the aerial environment. In well-structured, freely drained soils, the interstitial pores are gas-filled and interconnected with the atmosphere above the soil surface (Gambrell, Delaune & Patrick 1991). Consequently, plant roots are surrounded by a stable gaseous atmosphere virtually identical to that above ground (pO2: 20.8 kPa) (Greenwood 1970). As the soil becomes increasingly wet, pore spaces become water-filled and oxygen is depleted by biological and chemical oxidations. Large fluxes of gas cannot take place in the liquid phase; the diffusion of oxygen and carbon dioxide in water being 1/10000 the rate of diffusion into the gaseous soil atmosphere (Dwater/Dair: 1.13 × 10^-4) (Greenwood 1961; Grable 1966). Hence, further diffusion of gases into and out of the soil is restricted by the presence of free water in the pores and oxygen availability declines, whilst carbon dioxide and the products of microbial and root system respiration accumulate (Ponnamperuma 1984). Plants require metabolic and/or morphological adaptations to survive such conditions. Many of the latter are mediated via plant hormones, most notably ethylene (Jackson 1985, 1990; Voesenek et al. 1992).

In maize roots, there is evidence of causal relationships between oxygen supply, rate of ethylene biosynthesis and the extent of aerenchyma development. When nodal roots of maize were exposed to partial oxygen shortage, aerenchyma developed in the cortex, in association with faster ethylene production (Jackson 1982; Jackson et al. 1985). A similar increase in ethylene production was observed in roots of barley (Jackson et al. 1984) and in the stems of deep water rice (Mettraux & Kende 1983). However, not all plant tissues respond to oxygen deficiency in this manner. In mungbean hypocotyls (Imaseki, Watanabe & Odawara 1977), rice coleoptiles (Raskin & Kende 1983) and banana fruit (Banks 1985), ethylene evolution declines rather than increases with decreasing partial pressures of oxygen. Furthermore, ethylene biosynthesis requires molecular oxygen for the conversion of methylthioribose phosphate to
2-keto-4-methylthiobutyrate and for conversion of 1-
aminocyclopropane-1-carboxylic acid (ACC) to
ethylen (Yang & Hoffman 1984). Thus, the possibility
exists that the reported hypoxic stimulation of ethylene
production is an artifact. The problem may lie in
conventional techniques for measuring ethylene pro-
duction that rely on head space analysis by gas chroma-
tography of ethylene evolved by excised tissue enclosed
in small incubation vials. This is usually necessary to
accumulate sufficient gas for detection by gas chromatog-
raphs equipped with flame ionization detectors (FID) or
photoionization detectors (PID) which are only
sensitive to 10 mm⁻³ ethylene or more. Unfortunately,
such methods may distort ethylene production by
wounding, disruption of transport processes, graviti-
tropic disorientation and changes in gas composition
around the tissues. To avoid these problems, we
employed a laser-driven photoacoustic detector (PA-
detector), capable of measuring ethylene concentra-
tions down to 6 x 10⁻⁶ mm⁻³ in a gas stream flowing slowly
over roots of intact seedlings that were relatively
unperturbed by wounding, re-orientation and changes
in the gaseous environment caused by excision and
sealed enclosures.

MATERIALS AND METHODS

Preparation of plant material

Caryopses of maize (Zea mays L. cv. LG11) were
surface sterilized in 1% (v/v) sodium hypochlorite
solution for 10 min, rinsed thoroughly with distilled
water and imbibed for 24 h in 400 cm⁻³ of aerated, 0.5 mol
m⁻³ CaSO₄ solution. Imbibed caryopses were sown in
vermiculite dampened with 0.5 mol m⁻³ CaSO₄ in
90 x 90 x 50 mm opaque plastic trays covered with a
glass plate and germinated in the dark at 25°C. After
24 h, seedlings with radicles approximately 10 mm long
were washed gently with distilled water to remove
vermiculite dampened with 0.5 mol m⁻³ CaSO₄ in
90 x 90 x 50 mm opaque plastic trays covered with a
glass plate and germinated in the dark at 25°C. After
24 h, seedlings with radicles approximately 10 mm long
were washed gently with distilled water to remove
vermiculite and transplanted onto a perforated sheet of
aluminium foil.

Isolation of intact primary roots

Single seedlings with roots 20–30 mm long were sealed
into glass cuvettes (see Fig. 1 and Moss, Hall & Jackson
1988). Each cuvette consisted of two chambers. The
upper contained the caryopsis and damp vermiculite
into which secondary roots and coleoptile extended, and
was open to the ambient atmosphere. The primary root
was sealed in the lower chamber through which chosen
gas mixtures were passed. The lower chamber had an
internal volume of 14 x 10⁻⁶ m³ and contained
1–2 x 10⁻⁶ m³ of distilled water to ensure high internal
humidity. Seedlings were sealed into the cuvettes with a
slurry of plaster of Paris around the base of the radicle
(Fig. 1b). Once the plaster of Paris had set, a layer of
damp vermiculite was placed over the caryopsis and the
root compartment darkened by wrapping it with alumi-
nium foil.

Compressed air or oxygen in a balance of nitrogen
(Hoekloos, Schiedam, The Netherlands) was scrubbed
of trace hydrocarbon contaminants with a platinized
catalyst at 400 °C and with 'Ethysorb' (Stayfresh Ltd,
London, UK) to remove ethylene. Mixtures containing
carbon dioxide were passed through the platinized
catalyst alone, since Ethysorb also removes carbon
dioxide. Gases, flowing at 1 x 10⁻³ m³ h⁻¹, were
humidified before entering the cuvettes by bubbling
through distilled water in a sealed serum vial. Out-flow-
ing gases passed from the cuvettes into an eight-way
switching valve, where the gas streams to be measured
were directed in sequence into the PA-detector. Flows
not under measurement were vented into the atmos-
phere. Before entering the PA-detector, gases passed
over potassium hydroxide pellets to remove carbon
dioxide, and over CaCl₂ desiccant. Removal of carbon
dioxide and water is important since both interfere with
ethylene detection, increasing the background signal
and lowering the sensitivity of the apparatus. The gas
stream was also passed through a cold trap at −70 °C to
remove ethanol and other large molecular weight vola-
tiles, which may also interfere with PA detection of
ethylene. The apparatus was checked to ensure that low
partial pressures of ethylene were not frozen-out along
with ethanol in the cold trap.

The laser-driven intracavity photoacoustic
detector

Ethylene concentration in out-flowing gas streams from
the cuvettes was measured by a laser-driven PA-detec-
tor (Harren et al. 1990). Briefly, the detector operates as
follows. A mechanically-chopped carbon dioxide
waveguide laser beam is directed into a photoacoustic
cell (PA-cell) containing a gas sample. Ethylene in the
sample absorbs at the emission frequencies of the laser
(9–11 μm). Ethylene molecules are excited by the laser
beam from the ground state into a higher vibrational
state. de-excitation processes redistribute the energy
via collisions with other molecules in the gas sample,
causing an increase in the kinetic energy of the
molecules, and hence, a concurrent increase in
temperature. In a closed, resonant PA-cell, the increase
in temperature raises the pressure which, when modu-
lated at an audio frequency, can be detected by a
microphone. To maximize the microphone signal, a
mechanical beam-chopper was tuned to the resonance
frequency of the PA-cell, creating an acoustic `standing
wave' inside the resonator (length 100 mm; diameter
Ethylene production by hypoxic maize roots

Figure 1. (a) The primary root of a single, intact seedling of Zea mays sealed into a glass cuvette. The root was isolated in the lower chamber through which a humidified gas stream of known partial pressure of oxygen or carbon dioxide was passed. (b) Detail showing seedling sealed into the cuvette with plaster of Paris around the base of the caryopsis.

6 mm) of the PA-cell. To further increase the sensitivity, the PA-cell was enclosed within the laser cavity. The resultant high intracavity laser power (>100 W) enables detection of ethylene down to 0.041 pmol m⁻³ (Harren et al. 1990). The PA-detector was calibrated against known amounts of ethylene (0.003-0.0005 mm³) in air and the response was checked for linearity.

Ethylene measurement

Ethylene from two separate, single roots was measured in each treatment. A sealed cuvette without a root was included to provide a reference for changes in background. This background value also accounted for any trace contamination of inflowing gas mixtures with ethylene and was assumed to represent the zero baseline from which subsequent root production values were calculated. Experiments lasted approximately 28 h and involved measurements of ethylene from a single root and respective reference cuvette in each of two gas mixtures. In most cases, the first and last 6 h of the experiment were performed in air with the treatment mixtures supplied for the intervening 16 h. All times are approximate. Gas streams from root and empty (reference) cuvettes were measured consecutively over a period of 1 h, and the sampling order of the cuvettes was randomized.

Data manipulation and calculation of ethylene production rates

Root length, appearance and flow-rates were assessed at each change of treatment gas. Flow rates were adjusted as necessary to restore a rate of 1 x 10⁻³ m³ h⁻¹. Root fresh weight was measured at the end of each experiment. The mean initial fresh weight of roots was obtained from 10 roots of similar length to those in the cuvettes at the beginning of the experiment. Ethylene concentration in out-flowing gas streams was determined on the basis of the difference in laser signal (converted into equivalent cubic millimetres of ethylene) between root and reference cuvettes. Ethylene concentrations were converted into production rates (mm³ g⁻¹ fresh weight h⁻¹) which incorporated estimates of increases in root biomass based on changes in length. The relationship between length and
weight was calculated from each phase of the experiments (i.e. first 6h of air, 16h treatment period and second 6h of air). Each experiment was repeated two to five times with similar results. Representative data are presented.

Assessment of cortical aerenchyma

In a separate experiment, caryopses were germinated as described previously and seedlings with primary roots 20-30mm long transferred to opaque, acrylic boxes (6.6 x 10^-3 m^3). These allowed the primary roots of up to 10 intact seedlings to be treated with a flow of 3kPa O2 in a dark, moist atmosphere for 72h prior to analysis of cortical gas space. Precautions were taken to ensure that the portion of root analysed had completed its longitudinal growth phase before being exposed to the treatment and had not already responded to endogenous ethylene up to that time. This was accomplished by growing the seedling roots in an air atmosphere enriched with the volatile ethylene antagonist 2,5-norbornadiene (2 x 10^-4 m^3 m^-3; Aldrich Chemical Co. Ltd, Dorset, UK) for 48h. The roots were marked 10mm behind the tip with a slurry of charcoal powder after 24h, and again after 48h. The zone of root between the two marks was examined for aerenchyma after a further 72h in either air or 3kPa O2, flowing at 3 x 10^-3 m^3 h^-1. A 10-mm section from the middle of the marked zone was sectioned transversely with a razor blade and examined with a low-power microscope connected to a video camera and Optomax Model 5 image analyser (Analytical Measuring Systems, Cambridge, UK). The percentage area of the cortex that comprised intercellular space formed by cell collapse was scored.

RESULTS

Ethylene production

There were clear trends in ethylene production by primary roots of maize in response to different partial pressures of oxygen. Ethylene production in air (20-8 kPa O2) was high at the start of most experiments, but declined during the first 6h. When air was passed over the roots throughout the experiment, production continued to decline at a rate of approximately 0.00015 mm^3 h^-1 (Fig. 2a). Switching to 12.5 kPa O2 after 6h in air did not affect this pattern of decline during the next 16h and the resultant trends in air and 12.5 kPa O2 were more or less identical (Fig. 2b). However, treatment with 5kPa, 3kPa and probably 1kPa O2 caused ethylene production to increase (Fig. 2c,d,e). The most pronounced stimulation occurred in 3kPa O2, where levels increased within the first hour of treatment and remained at a high level 0.008-0.01 mm^3 g^-1 h^-1 for the entire 16-h treatment. The effect of 5kPa O2 was similar, but production gradually declined with time of exposure. A small stimulation of production was also apparent when roots were switched into 1kPa O2. Ethylene synthesis was arrested completely by the absence of oxygen (Fig. 2f). Ethylene production rates soon returned to normal when, after 16h in 5 or 3kPa O2, roots were returned to air. Production of ethylene after 16h of anoxia did not increase when the roots were returned to air, and remained at or close to zero for the remaining 6h of the experiment.

The possibility that carbon dioxide might interfere with the ability of the roots to produce ethylene in response to 3kPa O2 was tested by combining 3kPa O2 with either 0.1 or 10kPa CO2. These mixtures were supplied for 16h before the roots were returned to air. The marked decrease in ethylene production observed upon switching back to air (Fig. 3a) indicates that the difference in ethylene production in air or 3kPa O2 is retained in the presence of carbon dioxide. These partial pressures of carbon dioxide also failed to change rates of ethylene production in air (Fig. 3b).

Root elongation

Root extension was inhibited at all oxygen concentrations below 20-8 kPa, compared to aerobic controls (Fig. 4). At 12.5 kPa O2, extension rates were slowed from 1.50 mm h^-1 to 1.18 mm h^-1 (a reduction of 21%), while more severe inhibitions were obtained with smaller oxygen partial pressures. The 3 or 5 kPa O2 treatments gave extension rates of 0.46 and 0.41 mm h^-1, respectively, whilst 1 kPa reduced root growth to 0.29 mm h^-1, only 19% of the elongation rate in air. Almost no growth was observed in the complete absence of oxygen. In most cases, post-treatment root extension rates were similar to those observed during treatment (Fig. 4). However, after 16h of anoxia, no further growth was observed while recovery from 16h of 5kPa O2 was sufficient to raise rates of extension 2.5-fold to rates approaching those of roots given air throughout. Thus, treatment with partial pressures of oxygen less than 5kPa limited the competence of the roots to recover strongly during the first 6h after hypoxia.

Root morphology

Whilst roots exposed to anoxia, 1 kPa and 12.5 kPa O2 resembled those grown in air in all respects except root length, oxygen partial pressures of 3 and 5 kPa resulted in other changes in root morphology. These included swelling of tissue behind the root tip, proliferation of root hairs and plagiotropic deflection of the root tip (Fig. 5). When roots given 3kPa O2 for 72h were sectioned in a zone that lay 1 cm behind the root tip at the time treatments began, the extent of cortical collapse to form aerenchyma was considerably greater than that in roots grown in air (Table 1).

The morphology of tissue produced after returning to air was similar to air-grown roots, in all cases, except...
Figure 2. Ethylene production by roots of *Zea mays* exposed to various partial pressures of oxygen. All experiments commenced with an acclimatization period of approximately 6 h in air, followed by 16 h of treatment and lastly a second 6 h period in air to assess the response to a return to air. Representative data from the primary root of a single, intact seedling are displayed for each separate treatment. Each experiment was repeated two to five times with similar results. All data have been compensated against a reference gas-sample passed through an empty cuvette, to account for any changes in background or contamination of the gas-stream at source. Arrows indicate start and finish of the 16-h treatment period.
Figure 3. Effect on ethylene production by roots of *Zea mays* of (a) switching to air after 16-h exposure to 3 kPa O\(_2\) in the presence of 0-1 or 10 kPa CO\(_2\), or (b) switching to air after 16-h exposure to 0-1 or 10 kPa CO\(_2\) in air. Arrows indicate the time at which roots were returned to air: dashed arrows refer to 10 kPa CO\(_2\) treatments, and solid arrows to 0-1 kPa CO\(_2\) treatments.

Figure 4. Root extension (mm h\(^{-1}\)) of *Zea mays* seedlings during 16 h of treatment at the indicated partial pressure of oxygen, and during 6 h when roots were returned to air.
Ethylene production by hypoxic maize roots

Figure 5. Roots of *Zea mays* after 16h of treatment at various sub-ambient partial pressures of oxygen. Roots grown in 3 and 5 kPa O$_2$ are thickened, plagiotropic and have many root hairs compared to those grown in 12.5 and 1 kPa O$_2$. Roots in 12.5 kPa O$_2$ were slightly shorter but otherwise similar in appearance to roots grown in air throughout. Root lengths are not to scale.

Table 1. Aerenchyma as a percentage of cross-sectional area of the cortex of primary roots of 7-day-old *Zea mays* seedlings after 72h of treatment with either 3 or 20.8 kPa O$_2$ (air controls)*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Aerenchyma area (percentage of total cortical area)</th>
<th>±SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.8 kPa O$_2$</td>
<td>0.796</td>
<td>0.280</td>
</tr>
<tr>
<td>3.0 kPa O$_2$</td>
<td>11.863</td>
<td>2.006</td>
</tr>
</tbody>
</table>

* Means of several sections from each of 10 roots. Sections analysed were 24h old when first treated with 3 kPa O$_2$ or with air, and 96h old when sectioned.

DISCUSSION

The time-courses of ethylene emanation from single root axes of intact seedlings (the first of their kind) were made possible by the very high sensitivity of the laser detector to ethylene. The enclosure of roots in through-flow cuvettes ensured that the roots suffered a minimum of physical perturbation. Problems arising from the excision of segments that characterize the conventional headspace methodology were, thus, avoided. Nevertheless, ethylene production rates declined during the first 5h after transferring the seedlings to the flow-through cuvettes. We suppose that this early high production rate was a response to the, albeit gentle, procedures involved in transferring seedlings to the cuvettes. The enhanced rates may well have been physiologically significant since they were associated with the production of a short region of swollen tissue and prominent root hair production. Such features are typical ethylene effects on roots. In air (20.8 kPa O$_2$), the roots soon grew away normally, leaving behind a swollen segment marking the position of the root tip at the time of transfer. This subsequent normal growth was associated with a low but slowly declining rate of ethylene production. After 6h in air, roots transferred to 12.5 kPa O$_2$ for 16h also continued to form ethylene at slow rates. Therefore, the slightly slower rate of root extension by these roots cannot be attributable to any extra ethylene production. Instead the inhibition was probably a consequence of oxygen shortage inhibiting the action of oxidases (e.g. indole acetic acid oxidase) with low affinities for oxygen. The absence of swelling, root hair production and abnormal gravitropism supports the view that roots in 12.5 kPa O$_2$ produce insufficient ethylene for marked physiological activity. This finding differs slightly from that of previous experiments (Jackson et al. 1985) with excised segments of maize root tip,
that showed a small increase in ethylene when oxygen supply was reduced from 20.8 kPa to 12.5 kPa O2.

Evidence that oxygen partial pressures below 12.5 kPa can stimulate ethylene production is seen in (1) the marked upward shift in ethylene emission when the oxygen supply was lowered to 3 or 5 kPa O2 (Jackson et al. 1982; Jackson et al. 1985; Atwell, Drew & Jackson 1988). Although the increases in ethylene in the present study were smaller than previously reported, they appear to be sufficient for physiological activity since the roots quickly became swollen and plagiotropic while forming numerous root hairs. All these phenomena can be reproduced in maize roots by applying small amounts of ethylene in air (Bucher & Pilet 1982; Moss et al. 1988). Furthermore, when roots grown in air or 3 kPa O2 for 72 h were sectioned through 4-d-old tissue, the latter contained increased amounts of aerenchyma in the cortex. Previous studies with inhibitors of ethylene production have attributed aerenchyma formation in oxygen-deficient roots to the action of ethylene (Jackson et al. 1985).

The extent to which the extra ethylene formed in 3 or 5 kPa oxygen was responsible for inhibiting root elongation is not clear. Previous studies with roots of barley (Hordeum vulgare) indicated that a lack of oxygen rather than ethylene was the more important (Jackson et al. 1984).

There is a notable inconsistency between the present results and those of Jackson et al. (1985) with respect to the effects of 1 kPa O2. In the present work, decreasing oxygen partial pressures from those of air to 1 kPa did not change ethylene production substantially. A slight increase was seen, but there was no discernible decrease on returning to air. Previous work, with excised root segments showed a large promoting effect (Jackson et al. 1985). However, in accord with earlier findings, no evidence of physiological responses to ethylene were seen under these small oxygen partial pressures, i.e. no swelling or plagiotropism. The very slow rate of root extension and the lack of ethylene responsiveness of roots in 1 kPa O2 were probably consequences of metabolic lesions, especially to energy metabolism and unsaturated fatty acid synthesis, that could be expected to interfere with growth processes (Vartapetian, Malik & Lance 1978). However, measurements of root extension show clearly that such lesions were not sufficiently severe to stop growth completely. As little as 0.1 kPa O2 was found to be sufficient to sustain slight extension over 16 h (result not shown) and others have also shown that some root growth is possible provided only a very small amount of oxygen is present (Laan, Clement & Blom 1991; Waters et al. 1991). In our experiments, it was unlikely that the roots received any supplementary oxygen by internal transport from the shoots via aerenchyma since 16 h treatment was insufficient to enhance intracellular gas space formation. In their absence, the small, unconnected intercellular pores will be highly limiting to oxygen transport (Armstrong & Beckett 1985). Thus, we conclude that the stimulation of ethylene production by 1-10 kPa O2 previously reported was an artifact of the method employed.

Accumulation of carbon dioxide commonly occurs in flooded soils (Grable 1966) and within the roots of flooded plants, where it may influence ethylene production, metabolism and action (Smith et al. 1985; Sisler & Wood 1988; Hall 1991; Mattoo & White 1991), although the mechanisms are uncertain and probably various. However, little is known about the influence of elevated CO2 concentrations on root-ethylene production at low partial pressures of oxygen. Thus, it was important to check whether carbon dioxide could interfere with the response of maize roots to oxygen. Our results showed that an increase in carbon dioxide concentration to 0.1 or 10 kPa did not affect ethylene production rates in air or 3 kPa O2. Hence, the build-up of carbon dioxide in flooded soils is unlikely to interfere with increased ethylene production caused by partial oxygen shortage.

Since ethylene production is extinguished by anoxia there is, obviously, an absolute requirement for some molecular oxygen. Thus, the stimulation of ethylene production by partial oxygen shortage is something of a paradox. However, our results show unequivocally that such a stimulation occurs, and under our experimental conditions, is concomitant with changes in root morphology which may be associated causally with the presence of increased amounts of ethylene. The dependence on molecular oxygen, observed in our experiments, and the evidence of Jackson et al. (1985), that inhibitors of ACC-synthase, such as 1-aminoethoxyvinylglycine (AVG), suppress ethylene production during hypoxia, strongly suggest that biosynthesis in hypoxic maize roots occurs via ACC and the ethylene-forming enzyme complex (EFE). Furthermore, a positive correlation, during hypoxia, between endogenous ACC concentrations, ACC-synthase activity and ethylene production has been observed by several authors (Cohen & Kende 1987; Atwell et al. 1988; Wang & Arteca 1992), which suggests that synthesis in oxygen-deficient cells may be regulated by ACC-synthase. This could be brought about by enhanced transcription of one or more genes coding for ACC-synthase, by post-translational modification of existing mRNA, or by modification of an inactive form of the enzyme. The possibility of downregulated polyamine biosynthesis releasing additional S-adenosyl methionine for conversion to ACC has been discounted by Jackson & Hall (1993). The ACC oxidizing EFE is thought to be a dioxygenase with considerable sequence homology to flavanone 3-hydroxylase (Hamilton, Lycett & Grierson 1990; Ververidis & John 1991), and its action to be absolutely dependent on molecular oxygen (McKeon & Yang 1987). According
to McGarvey & Christoffersen (1992), the $K_m$ of EFE from avocado fruit for oxygen is $4.6 \pm 0.8$ kPa. Therefore, assuming that EFE from maize roots has a similar $K_m$, its activity at 3 kPa O$_2$ would be less than half of that in air. However, EFE appears to be present in quantities in excess of those required to convert the additional ACC to ethylene, since the capacity of roots exposed to 3 kPa O$_2$ to convert exogenous ACC is similar to that in air (Atwell et al. 1988).

The complete picture may need to take into account spatial separation of the sites of ACC synthesis and its oxidation to ethylene. For example, ACC may accumulate in the anoxic root tip or stele (Jackson 1989) as a result of increased ACC synthase production (Wang & Arteca 1992) or activity. The extra ACC produced in this way may then diffuse into better aerated cortical tissues where it is converted to ethylene in the presence of small amounts of oxygen. Further work is needed to clarify some of these possibilities.

**ACKNOWLEDGMENTS**

The authors thank F. J. M. Harren, C. Sikkens and J. Reuss (Department of Molecular and Laser Physics), G. M. Bögemann and C. M. Mudde (Department of Ecology) of the University of Nijmegen for their help. We also thank P. J. A. Vervuren and C. W. C. J. van de Rijt for valued contributions, and N. M. Western for the use of the Optomax image analyser. This work was supported financially by the Science and Engineering Research Council (UK) through a CASE studentship to RWB, by the Agricultural and Food Research Council (UK) through its ‘Collaboration with the Netherlands Communities’ Eclair Programme and by the Commission of European Communities’ Eclair Programme.

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Received 15 March 1993; received in revised form 3 June 1993; accepted for publication 24 June 1993