Root hydraulic conductance: diurnal aquaporin expression and the effects of nutrient stress

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Abstract

It has been shown that N-, P- and S-deficiencies result in major reductions of root hydraulic conductivity (Lp) which may lead to lowered stomatal conductance, but the relationship between the two conductance changes is not understood. In a variety of species, Lp decreases in the early stages of NO3−, H2PO4− and SO4−2 deprivation. These effects can be reversed in 4–24 h after the deficient nutrient is re-supplied. Diurnal fluctuations of root Lp have also been found in some species, and an example of this is given for Lotus japonicus. In nutrient-sufficient wheat plants, root Lp is extremely sensitive to brief treatments with HgCl2; these effects are completely reversible when Hg is removed. The low values of Lp in N- or P-deprived roots of wheat are not affected by Hg treatments. The properties of plasma membrane (PM) vesicles from wheat roots are also affected by NO3−-deprivation of the intact plants. The osmotic permeability of vesicles from N-deprived roots is much lower than that of roots adequately supplied with NO3−, and is insensitive to Hg treatment. In roots of L. japonicus, gene transcripts are found which have a strong homology to those encoding the PIP1 and PIP2 aquaporins of Arabidopsis. There is a very marked diurnal cycle in the abundance of mRNAs of aquaporin gene homologues in roots of L. japonicus. The maxima and minima appear to anticipate the diurnal fluctuations in Lp, by 2–4 h. The temporal similarity between the cycles of the abundance of the mRNAs and root Lp, is most striking. The aquaporin encoded by AtPIP1 is known to have its water permeation blocked by Hg binding. The lack of Hg-sensitivity in roots and PMs from N-deprived roots provides circumstantial evidence that lowered root Lp may be due to a decrease in either the activity of water channels or their density in the PM. It is concluded that roots are capable, by means completely unknown, of monitoring the nutrient content of the solution in the root apoplast and of initiating responses that anticipate by hours or days any metabolic disturbances caused by nutrient deficiencies. It is the incoming nutrient supply that is registered as deficient, not the plant’s nutrient status. At some point, close to the initiation of these responses, changes in water channel activity may be involved, but the manner in which monitoring of nutrient stress is transduced into an hydraulic response is also unknown.

Key words: Lotus japonicus, hydraulic conductivity, diurnal cycle, aquaporin, root, plasma membrane.

Introduction

A plant can have its transpiration, stomatal conductance (Gt) and root hydraulic conductivity (Lp) influenced strongly by its supply of certain mineral nutrients. This much has been recognized for many years (Desai, 1937), but while it is agreed that these responses occur without there being any gross perturbation in leaf water status, they are not completely explained. When they are deficient in the growth medium, three plant nutrients, nitrate,
phosphate and sulphate, which are transported, metabolized and utilized in different ways, all produce similar effects on \( G_e \) and \( Lp_t \). It seems improbable that these effects are caused by completely separate sequences of events. Thus, one should not, for instance, expect to explain stomatal closure in P-deficient plants solely by reference to P-metabolism or tissue distribution of P; when there is no P-limitation, \( G_e \) is equally sensitive to N-deficiency and S-deficiency. Similarly, root \( Lp_t \) is strongly responsive to the N supply, but it may also be affected by P and S deficiency (Radin and Eidenbock, 1984; Karmoker et al., 1991). One might ask, therefore, whether stomatal closure and diminished \( Lp_t \) are central objectives of the nutrient-stress response, elicited by some common sequence of events. The idea that there may be a centralized stress response system had already been advanced (Chapin, 1990).

It is important to consider the timing of events and the order in which they unfold. In Fig. 1 the sequence has been divided arbitrarily into two branches: the first embraces nutrient-specific responses of transport systems, while the second, more general branch, is concerned with hydraulic and morphological events. It must be stressed that this scheme of things, particularly in the general branch, is speculative. The response of plants to potassium deficiency seems to be restricted to the specific branch. As with other nutrient deficiencies, K-deprivation de-represses K transport systems in roots, appearing to make the root a more avid absorber of K from dilute solutions. But, unlike N, P or S deficiency, K does not appear to influence the events in the general branch. In itself, this is a most interesting issue but not one which can be treated in this short paper.

In this paper the hypothesis is advanced that anion fluxes (in which energized transport dominates the overall process) are linked with the hydraulic conductivity \( (Lp) \) of root plasma membranes (PM), possibly through the activity of water channels. The essence of this idea is that nutritional information is transduced into an hydraulic response.

### Nutrient deficiencies and water relations of crop plants

There were a number of early reports that certain nutrient deficiencies resulted in partial or complete stomatal closure in plants adequately supplied with water (Desai, 1937; Wallace and Frohlich, 1965). In more recent times, the work of John Radin and his colleagues has given the clearest insights into the relationships between N and P nutrition, stomatal conductance and leaf expansion. Work with cotton plants, grown in a controlled environment, revealed that both N- and P-deficient conditions restricted leaf expansion, reduced transpiration and decreased the hydraulic conductivity of the plants, without there being any effect on leaf water potential (Radin and Ackerson, 1981; Radin and Eidenbock, 1984). With P-deficient plants it was established that the root was the site of diminished hydraulic conductance and that this could be detected well in advance of measurable effects on leaf expansion (Radin and Eidenbock, 1984), but that the effect on \( Lp_t \) diminished if the temperature of the roots was increased to values >30 °C (Radin, 1990). A cell pressure probe, inserted into cortical cells of cotton roots, showed the \( Lp \) of the PM was smaller, than in nutrient-sufficient controls, by approximately 60% and 85% in P- and N-stressed plants, respectively. The effects could be picked up within 1 d of N-deprivation (Radin and Matthews, 1989).

N-deficiency in barley and tomato plants lowered \( Lp_t \) in advance of effects on \( G_e \) and photosynthesis (Chapin et al., 1988). In barley, it was found that S-deprivation diminished root \( Lp_t \) progressively over 4 d to a value <20% of S-replete controls (Karmoker et al., 1991); these effects preceded reductions in transpiration and net assimilation rate (Gilbert et al., 1997). In wheat plants, effects on root \( Lp_t \), caused by N- and P-deprivation, were quickly reversed when nutrient supplies were resumed (Carvajal et al., 1996). Rapid reversibility of effects on \( Lp_t \) have been reported in Zea mays when N-starved roots were supplied with either NO\(_3^-\) or NH\(_4^+\); the effect being dependent on NO\(_3^-\) reduction (Barthes et al., 1996).

In summary it can be said that depriving plants of...
adequate supplies of the three major nutrient anions results in a prompt diminution of cell and root hydraulic conductivity which is fully reversible when the nutrient supply is restored. Effects can be detected before those on photosynthesis, but may be concomitant with the slowing of leaf expansion. The authors are not aware of any report that K-deficiency affects root $Lp_r$.

**Nutrient deficiencies and root growth**

It has been observed frequently that plants which are N- or P-limited in their growth allocate a greater proportion of their total assimilated carbon to root growth (Robinson, 1994). Not all species respond in this way and examples can be found of closely related ones which behave differently, for example, *Plantago* spp. (Lambers et al., 1981a, b) and *Agropyron* spp. (Jackson and Caldwell, 1989). The relative expansion of the root system when plants experience scarcity of an essential nutrient conforms to a commonsense notion that this is a ‘sensible’ strategy to maximize resource capture below ground. It has been questioned, however, whether or not this is as sensible as it appears at first, especially in the case of N-deficiency (Robinson, 1996). Nitrate is free to diffuse towards root surfaces and will do so more rapidly if influx at the root surface is increased. Following this logic there is no ‘need’ to expand the root surface, an increase in absorption rate should increase the rate at which NO$_3^−$ diffuse to the root surface, and yet the effect is very widely seen. When conditions of N-supply are shifted from a sufficient to a sub-sufficient level there is usually a period during which the root:shoot weight ratio increases, but, after some time, it reaches a new steady value (for example, in young plants of *Betula pendula*, McDonald et al., 1986).

Local sources of N (both as NO$_3^−$ or NH$_4^+$) or P, in media which are generally nutrient deficient, elicit local root proliferation (Drew and Saker, 1975, 1978). The nutrient absorption that occurs in the zone where roots proliferate can compensate, to some extent, for deficiencies in other root zones. Much work of this kind has been reviewed (Robinson, 1994). Interestingly, neither the root:shoot ratio response nor the localized proliferation of roots is elicited by K-deficiency. It should be noted, however, that S-deprivation in barley, while de-repressing sulphate transporter genes (Smith et al., 1998) and causing a major diminution of $Lp_r$, had relatively little effect on the root:shoot ratio (Karmokar et al., 1991). There is, therefore, no invariable linkage between the various effects in the general branch of Fig 1.

**Root $Lp_r$ and transpiration**

The apparent value of root $Lp_r$ has been reported to increase with transpiration rate (Mees and Weatherley, 1957; Passioura and Tanner, 1985). This phenomenon has been interpreted in several ways, but all of them fall short of describing, in molecular terms, a resistance which decreases as flow increases. Explanations in terms of additive effects of osmotic and hydrostatic driving forces (Fiscus, 1975), or of changes in the dominant pathways for the lateral movement of water across the root cylinder (Steudle, 1994; Steudle and Peterson, 1998) have been advanced as alternatives or have been incorporated into models in which effects of different pathways are compensatory (Steudle and Peterson, 1998). In these models, however, the role of water transport across root cell membranes remains to be quantified, although there have been attempts in which water relations have been worked out in great detail at the cell and root level (Zhu and Steudle, 1991; Azaiez et al., 1992). In these studies, cell $Lp$ appeared to be quite variable. The discovery of aquaporins in tonoplast and plasma membranes (Daniels et al., 1994; Kammerloher et al., 1994) and the demonstration that some of them at least, do function as PM water channels (Kammerloher et al., 1994; Kaldenhoff et al., 1998; Tyerman et al., 1999) provides an opportunity to see if they play a role in the apparent variability of $Lp_r$.

Both transpiration rate and $Lp_r$ have been found to vary diurnally, but a simple cause and effect was seemingly ruled out in a classic experiment (Parsons and Kramer, 1974) which showed that the diurnal rhythm continued for several cycles after root systems of cotton had been excised; the phases of the rhythm seemed to be set by the onset of light. In some of the experiments summarized below, it is shown that there are also diurnal cycles in the expression of mRNAs which are homologous to those encoding *Arabidopsis* aquaporins, but that their abundance is not influenced by concurrent transpiration rate.

**Behaviour of wheat roots during N- and P-deprivation**

Both N- and P-deprivation decreased the apparent value of $Lp_r$ in excised wheat roots (Carvajal et al., 1996); in these experiments the flow of water was driven by osmotic pressure differences between the xylem sap and the solution in the root apoplast. The measurements were made, therefore, at low rates of water flow, equivalent to, or less than those normally occurring during the dark period. A marked diurnal fluctuation in the value of root $Lp_r$ was found in plants sampled at different times during day and night; the amplitude of the cycle was much reduced by N- or P-deprivation, but remained significant (Table 1). If the roots of wheat plants were divided between solutions containing, or lacking NO$_3^−$, those in the −NO$_3^−$ half had lower root $Lp_r$ than those in the +NO$_3^−$ half (Carvajal et al., 1996).

Root $Lp_r$ was extremely sensitive to brief exposure to 50 μM HgCl$_2$. The inhibition was removed when roots
were unresponsive to treatment with Hg (from Carvajal et al., 1996). Mercury can hardly be thought of as a very specific inhibitor, especially when high concentrations are applied to tissues, but, if $L_{p}$ decreased because of a general metabolic blockade by Hg, rather than because of a direct interaction of Hg with water channels, one would expect to see a similar proportional collapse in $L_{p}$ in control and nutrient-deprived roots. This did not happen, even though, for example, Hg would be expected to have some effect on membrane potential. There is a report in the literature that water-flow through roots of tomato, driven by an applied external pressure, was severely inhibited by 500 μM HgCl$_2$ (Maggio and Joly, 1995). Where relatively great rates of water flow are measured, interactions of Hg with ion transport to the xylem may be less important.

In an attempt to resolve this question of whether or not there can be a direct interaction between Hg and water conductance, PM was prepared from wheat roots grown for 4 d with or without NO$_3$ in the culture medium, and their rate of shrinkage during exposure to hypertonic solutions was observed. Changes in volume, monitored by changes in light scattering at 500 nm in suspensions of PM vesicles, are very rapid and can be observed only with stopped-flow spectrophotometry. This technique has been explored rigorously by other researchers (Maurel et al., 1997; Niemietz and Tyerman, 1997). Figure 3a and b show the time-course of vesicle shrinking in PM vesicles from control and N-deprived roots. The initial rate, determined graphically, was much slower in the PM from N-deprived roots. This difference was maintained over a temperature range of 15−30 °C (data not shown). The initial rate of shrinkage was slowed down by approximately 50% by the treatment of control PM with 50 μM HgCl$_2$ for 5 min prior to osmotic challenge. There was no effect on the slower shrinking rate of the PM vesicles from N-deprived roots (Table 2). PM and tonoplast vesicles from wheat roots have been studied (Niemietz and Tyerman, 1997), but, in this case, the water permeability of PM vesicles was not Hg-sensitive; the difference between their results and the results of this study may be related to the nitrate-free medium used to grow their plant material. The cultured tobacco cells used by Maurel et al. (Maurel et al., 1997) to prepare membranes were exposed to high concentrations of nitrate in Murashige and Skoog medium, but were obviously habituated to conditions where water fluxes across the PM would have been low; these too showed little or no response to Hg, suggesting the absence of sensitive water channels.

### Studies of root $L_p$, in *Lotus japonicus*

*Lotus japonicus* can be used to study both diurnal and nutritional responses of $L_p$. A well-marked diurnal cycle of $L_p$ can be observed when root systems are enclosed.
The same cycle was found in plants transpiring \( \text{HgCl}_2 \) reduced (Table 3). The effect of withdrawing nitrate from and Steudle, 1995) also indicates that root aquaporins in water fluxes. There is at least one major class of aquaporin which lacks mercury sensitivity (for which distinguish PIP1-type aquaporins from others.

Nitrate-deprivation decreased strongly the abundance of PIP1-homologous mRNAs in half of the experiments, but had weaker effects in others. At present there is no explanation for this variable response which contrasts so markedly with the reproducible diurnal pattern.

Western blots of proteins isolated from the PM of \( L. \) japonicus reveal a single highly abundant band which cross reacts with anti-AtPIP1a antiserum. The antibody was raised against 42 N-terminal amino acid residues of L. japonicus glutamine synthetase and a homologue of the barley high affinity nitrate transporter HvNRT2 (Trueman et al., 1996); these show little diurnal cycling. As might be expected from the results in Table 3, current rates of transpiration had no effect on the abundance of the PIP1-homologous mRNA (Fig. 6).

Water permeability of the PM is lowered to between 20–30% of its activity in the absence of nitrate, and this decrease is also associated with calcium influx into the root apoplasm (Van der Leij et al., 1998). After 24 h the vacuolar \( \text{NO}_3^- \) in \( L. \) roots would have been largely dissipated (A Massonneau, unpublished data).

When mRNA from \( L. \) japonicus roots was probed with cDNAs to \( \text{AtPIP1} \) and \( \text{AtPIP2} \), strongly hybridizing transcripts were found (Clarkson et al., 1996; RN Waterhouse and AJ Smyth, unpublished results) whose abundance varied diurnally (Fig. 5). Transcript abundances increased to a maximum in the first part of the photoperiod, then declined to a minimum value at the beginning of darkness. The transcript abundance increased at the end of the night, thus anticipating dawn and the daytime increase in transpiration. Figure 5 also shows Northern blots of transcripts of the root-expressed cytosolic form of \( L. \) japonicus glucose synthetase and a homologue of the barley high affinity nitrate transporter HvNRT2 (Trueman et al., 1996); these show little diurnal cycling. As might be expected from the results in Table 3, current rates of transpiration had no effect on the abundance of the PIP1-homologous mRNA (Fig. 6).

Western blots of proteins isolated from the PM of \( L. \) japonicus reveal a single highly abundant band which cross reacts with anti-AtPIP1a antiserum. The antibody was raised against 42 N-terminal amino acid residues which distinguish PIP1-type aquaporins from others (Clarkson et al., 1996). The apparent MW of this band, 27–29 kDa, is characteristic of aquaporins.

### Water channels and variable root \( \text{Lp} \),

In \( L. \) japonicus there is strong evidence that the PM contains one or more aquaporins which are homologous to the PPI and PIP2 types of \( A. \) thaliana. It has been proved that \( \text{AtPIP1} \) in that species is an \( \text{Hg} \)-sensitive water channel; if the expression of the \( \text{PIP1} \) gene is down-regulated by antisense in \( A. \) thaliana, the water permeability of the PM is lowered to between 20–30% of that in wild type roots. Water permeability was inhibited by >90% by treatment of protoplast membranes with \( \text{HgCl}_2 \) (Kaldenhoff et al., 1998). The evidence from wheat roots (Carvajal et al., 1996) and from \( \text{Chara} \) (Henzler and Steudle, 1995) also indicates that root \( \text{Lp} \), and \( \text{Lp} \) of the PM, respectively, are extremely sensitive to brief \( \text{Hg} \) exposures. However, sensitivity of water permeation to \( \text{HgCl}_2 \) may not be a reliable guide to the involvement of aquaporins in water fluxes. There is at least one major class of aquaporin which lacks mercury sensitivity (for
Table 3. Diurnal variation of \( L_p \) in roots of *Lotus japonicus* transpiring at ambient or reduced rates

Measured under an applied pressure to root systems of 0.4 MPa.

<table>
<thead>
<tr>
<th>Point in cycle</th>
<th>Root hydraulic conductance (( \text{mg g}^{-1} \text{ root FW h}^{-1} \text{ MPa}^{-1} ))</th>
<th>(log, transformed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient transpiration</td>
<td>Reduced transpiration</td>
</tr>
<tr>
<td>Noon</td>
<td>2089</td>
<td>7.664</td>
</tr>
<tr>
<td>Mid-afternoon</td>
<td>1800</td>
<td>7.496</td>
</tr>
<tr>
<td>End of day</td>
<td>484</td>
<td>6.182</td>
</tr>
<tr>
<td>Pre-dawn</td>
<td>710</td>
<td>6.365</td>
</tr>
<tr>
<td>Mid-morning</td>
<td>1374</td>
<td>7.225</td>
</tr>
</tbody>
</table>

LSD \((P=0.05)\) between log, transformed means = 0.447 (based on 34 d.f.): four plants from each treatment were used for measurements at each time of day. Plants were grown in mist culture (Waterhouse et al., 1996); transpiration was reduced by placing transparent covers over the plants. Excised root systems were placed in a pressure chamber and measurements of water flow made for two 30 min periods (data from DT Clarkson unpublished results).

Fig. 5. Northern blots of mRNA from *Lotus japonicus* hybridized to cDNAs from two types of *Arabidopsis* aquaporin genes. Samples taken at different times of day and night. Results from hybridizations to cytosolic glutamine synthetase and a *Lotus* homologue of the barley high affinity nitrate transporter are shown for comparison; they show that diurnal cycling is not characteristic of all mRNAs. (Adapted from T Henzler et al., unpublished results.)

Fig. 6. Northern blots of mRNA from roots of *Lotus japonicus* sampled at different times of day. Low transpiration was achieved by covering the shoots with transparent covers; H refers to plants transpiring in ambient conditions in a greenhouse. Blots were probed with cDNA to AtPIP1. (From T Henzler et al., unpublished results.)

Example, RD28, Daniels et al., 1994). Clearly, in a membrane where such an aquaporin is the dominant water channel, there would be no Hg-sensitivity. It was found that water permeability of PM vesicles prepared from cultured tobacco cells was not Hg sensitive (Maurel et al., 1997). Moreover, these authors observed that the temperature dependence and activation energy of water transport in these preparations were not significantly different from values to be expected by simple diffusion.
of water across the lipid bilayer. From this they concluded that no case could be made for water channels having an important role in PM water permeability in their preparations. In *A. thaliana*, it has been pointed out that if there are Hg-insensitive aquaporins present in root PMs from NO$_3^-$-fed plants, they, and the diffuse permeability of the PM to water account for no more than 15% of the total permeability (Kaldenhoff *et al.*, 1998). It has also been shown that Hg has no effect on the diffusive water permeation of tobacco PM (Maurel *et al.*, 1997). This study’s results with NO$_3^-$-grown roots of wheat are more in agreement with those of Kaldenhoff *et al.* (Kaldenhoff *et al.*, 1998). The loss of Hg-sensitivity of root $L_p$, after N- or P-deprivation suggests that either the activity or the density of water channels in the root cell PMs is diminished during nutrient deficiency. This idea has also been advanced to explain changes in the hydraulic properties of roots of *Zea mays* with various levels and types of N nutrition (Barthes *et al.*, 1995, 1996; Hoarau *et al.*, 1996).

It should be borne in mind that changes in the contribution of the apoplastic pathway to the overall water conduction by the root may contribute to the observed fluctuation in root $L_p$ (Zimmermann and Steudle, 1998). In particular, water flowing through apoplastic leaks in younger parts of the root, or at the points of lateral root insertion, may increase root $L_p$ at higher flow rates. Nevertheless, it is suggested that the opening and closing of water channels will modify the relative rates of flow in the cell-to-cell and apoplastic pathways (Zimmermann and Steudle, 1998).

During P-deficiency observations on cytosolic Pi levels by $^{31}$P-NMR show that it is strongly buffered by vacuolar reserves (Lee and Ratcliffe, 1993). Similar homeostasis in cytosolic NO$_3^-$ has been observed in the first few days of N-deprivation in barley (van der Leij *et al.*, 1998). If there is little change in the concentration of these anions on the cytosolic side of the PM during the early stage of nutrient-deprivation, it is possible that the responses seen are due to changes in the composition of the solution in the apoplasma, i.e. at the extracellular face of the PM. It is by no means clear how such a response might be brought about; there might be some regulatory interaction, perhaps by phosphorylation (Johansson *et al.*, 1996), between ion movement through the anion transporters and either the activity or turnover of water channel proteins. In short, it may be that ion currents through these anion transporters is the message to which the system responds. Against this idea must be set the observations of Barthes *et al.* (Barthes *et al.*, 1996) that the increased $L_p$ in roots of *Z. mays*, seen when they are moved from a N-deficient medium to one containing nitrate, depended on nitrate reduction. One must conclude that the signal, in this instance, came from the cytoplasm where nitrate reduction occurs. A signal derived from nitrate or ammonium assimilation cannot explain, however, the strikingly similar effects of P-, S- and N-deficiencies on $L_p$. Perhaps there are, indeed, parallel pathways leading to the effect on $L_p$.

**Downstream effects of changing $L_p$.**

Much evidence is against the view that the stress-induced changes in $L_p$, grossly or permanently perturb plant water relations. Some of the earliest observations showed that stomata closed without there being any reduction in leaf water status (Chapin *et al.*, 1988). These results call to mind similar effects on stomata in plants where soil begins to dry; where some form of chemical signalling between roots and leaves has been advanced to explain these effects (Davies and Zhang, 1991; Davies *et al.*, 1994; Passioura, 1988; Schurr and Schultz, 1996). Both abscisic acid (Davies and Zhang, 1991) and unknown components of the xylem sap (Munns and King, 1988; Munns *et al.*, 1993) have been shown to increase in concentration in the transpiration stream of plants with roots in drying soil. The stomata close without there being a perturbation in leaf water potential. The signal for the increased release of stomata-closing substances from the root may be some change in root water potential or root turgor pressure. In the case of N-deficiency there are changes in the flux of two plant growth regulators from roots to leaves, namely abscisic acid, the concentration of which has been reported to go up in some species (Krauss, 1978; Clarkson and Touraine, 1994), but not in others (Peuke *et al.*, 1994) and cytokinin, the concentration of which goes down (Beck and Wagner, 1994). At present there is no basis upon which these changes in flux might be related to decreased $L_p$. It is well known, however, that ABA can increase $L_p$ if applied exogenously to roots (Hose and Hartung, 1999).

As mentioned earlier, another frequent response to N- and P-deprivation is increased allocation of dry matter to root growth. This response is also seen during drought stress in *Lolium perenne* (Jupp and Newman, 1987), *Zea mays* (Schmidhalter *et al.*, 1998), *Glycine max* (Huck *et al.*, 1983) among many other species of economic interest. In experiments with *A. thaliana*, lines carrying antisense constructs to *PIP1B* were found to have their root systems, both relatively and absolutely enlarged (Kaldenhoff *et al.*, 1998); there was no evidence of alteration in transpiration rate or shoot growth. The $L_p$ of the roots of *Arabidopsis*, and of the protoplasts derived from them, was diminished to about the same extent as found for N- and P-deprivation in wheat roots. In all lines, this decline was associated with more extensive root systems; in some cases five times as extensive as those of wild-type plants without there having been a major reduction in shoot size (R. Kaldenhoff, personal communication). It seems likely...
that the net assimilation rate of the leaves was increased in the antisensed lines to cope with the additional demands created by the growth and maintenance of such a large root system. It has been argued that the carbon costs of extensive root systems are negligible when set against nutritional gains or increased competitiveness (Thomas, 1994).

The intrinsic size of the root system of wheat genotypes may be genetically linked to drought and salinity tolerance; this was indicated by QTL analysis of a mapping population of doubled haploid lines arising for a cross of cv. Chinese spring × SQ1 (Chinoy et al., 1998). Lines tolerant of these stresses may also have more efficient nitrogen acquisition than those with relatively smaller, or shorter root systems (DT Clarkson and S Quarrie, unpublished results). The enlargement of the root system in 24 independently transformed lines of Arabidopsis thaliana carrying antisense to PIP1b suggests a relatively simple manipulation for increasing stress tolerance if other species of economic interest are found to behave similarly. The Arabidopsis plants in earlier experiments (Kaldenhoff et al., 1998) behaved as if they had detected hydric or nutrient stress without developing any adverse symptoms.

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