Calculated activity of Mn$^{2+}$ at the outer surface of the root cell plasma membrane governs Mn nutrition of cowpea seedlings

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Abstract

Manganese (Mn) is an essential micronutrient for plant growth but is often toxic in acid or waterlogged soils. Using cowpea (Vigna unguiculata L. Walp.) grown with 0.05–1500 μM Mn in solution, two short-term (48 h) solution culture experiments examined if the effects of cations (Ca, Mg, Na, Al, or H) on Mn nutrition are related to the root cells' plasma membrane (PM) surface potential, $\psi_0$. When grown in solutions containing levels of Mn that were toxic, both relative root elongation rate (RRER) and root tissue Mn concentration were more closely related to the activity of Mn$^{2+}$ at the outer surface of the PM, $\{\text{Mn}^{2+}\}_0$ ($R^2=0.812$ and 0.871) than to its activity in the bulk solution, $\{\text{Mn}^{2+}\}_b$ ($R^2=0.673$ and 0.769). This was also evident at lower levels of Mn (0.05–10 μM) relevant to studies investigating Mn as an essential micronutrient ($R^2=0.791$ versus 0.590). In addition, changes in the electrical driving force for ion transport across the PM influenced both RRER and the Mn concentration in roots. The $\{\text{Mn}^{2+}\}_b$ causing a 50% reduction in root growth was found to be c. 500 to $>1000$ μM (depending upon solution composition), whilst the corresponding value was 3300 μM when related to $\{\text{Mn}^{2+}\}_0$. Although specific effects such as competition are not precluded, the data emphasize the importance of non-specific electrostatic effects in the Mn nutrition of cowpea seedlings over a $1\times10^5$-fold range of Mn concentration in solution.

Key words: Manganese nutrition, manganese toxicity, plasma membrane surface potential, root growth, tissue concentration.

Introduction

Manganese (Mn) is an essential micronutrient for the growth of plants, with Mn deficiency often occurring in plants grown on alkaline soils. By contrast, Mn toxicity is an important growth-limiting factor in the acidic soils that comprise c. 3.95 billion ha of the global ice-free land or 40% of the world’s arable land (Eswaran et al., 1997). Waterlogged soils also often contain high plant-available Mn (Setter et al., 2009). Toxicity of Mn to plants results from excess accumulation in leaves (Wissemeier et al., 1992), but adverse effects of Mn on root growth also occur. Furthermore, uptake of Mn by roots precedes accumulation in the leaves.

It has long been known that variation in the concentrations of cations, such as Ca and Mg, influence the availability of Mn to plants (Vlamis and Williams, 1962; Hauck et al., 2002). Alam et al. (2006) reported that increased Ca reduced Mn uptake and, hence, its toxicity in barley (Hordeum vulgare L.). The mechanism by which cations reduce the uptake of Mn (and that of other trace metals such as Cu, Ni, or Zn) is not known with certainty, but is commonly
assumed to be due to competition as described, for example, in the biotic ligand model (De Schampaephare and Janssen, 2002; Paquin et al., 2002). In the context of the present study, this model would relate plant growth to the activity of Mn\(^{2+}\) in the bulk solution, \(\{\text{Mn}^{2+}\}_b\). However, it has been shown that ionic effects on plant growth are often dependent upon the activity of the ion at the outer surface of the root cells’ plasma membrane (PM) (see Table 5 of Kinraide and Wang, 2010, for examples). The PM outer surface generally has a negative surface potential, \(\psi_0\), increasing the activity of cations and decreasing that of anions in close proximity to it (Kinraide, 2006). Mn-nutritional studies would, therefore, relate plant growth to the activity of Mn\(^{2+}\) at the outer surface of the root cells’ PM, designated as \(\{\text{Mn}^{2+}\}_0\). The cell wall also has a negative charge, although it appears that this has comparatively little influence on \(\psi_0\) and ion concentrations at the PM surface (Gage et al., 1985; Shomer et al., 2003; Kinraide, 2004).

This study examined the effects of cations on the calculated electrical properties of the PM to test the hypothesis that plant growth is more closely related to \(\{\text{Mn}^{2+}\}_0\) to that of \(\{\text{Mn}^{2+}\}_b\). Root growth and Mn concentration in roots were determined in two short-term solution culture experiments using cowpea (Vigna unguiculata L. Walp.). Calculated \(\{\text{Mn}^{2+}\}_b\) and \(\{\text{Mn}^{2+}\}_0\) were based on concentrations of Mn and other cations in solution (Kinraide, 2006). The two experiments separately investigated Mn concentrations considered adequate or excessive for cowpea root growth; the short-term nature of the experiments precluded investigation of the deficient range.

### Materials and methods

Experiments were conducted in a laboratory maintained at 25 °C at The University of Queensland, St Lucia, Australia. The experimental system has been used previously (Kopittke et al., 2008, 2009), but is briefly described here. Seeds of cowpea (cv. white Caloona) were rolled in paper towel and moistened with tap water for 3 d. The seedlings were then removed, placed in Perspex strips on top of 600 ml glass beakers filled to the brim (650 ml) with a continuously aerated solution of 1 mM CaCl\(_2\) and 5 \(\mu\)M H\(_3\)BO\(_3\). After 18 h, the roots were transferred to continuously aerated treatment solutions for a further 48 h. Root length was determined by taking photographs both at the time of transfer (0 h) and after 48 h. Previous investigations using this experimental system have shown that the elongation rate (RER) of roots growing in Ca-sufficient and toxicant-free solutions remain relatively constant during the 48 h experimental period (Kopittke et al., 2009).

Experiment 1 investigated the effects of cations (Ca, Mg, Na, H, and Al) on root growth and on the concentration of Mn in roots at solution concentrations of Mn relevant for toxicity. All solutions contained >2.0 mM \(\{\text{Ca}\}_0\) to prevent a decrease in root growth due to Ca deficiency (Kopittke et al., 2011). Five Mn concentrations were imposed, 1, 250, 650, 1000, and 1500 \(\mu\)M. Because Mn toxicity results from excess accumulation in leaves (Nable and Loneragan, 1984), the Mn concentrations used were higher than those shown to be phytotoxic in longer-term experiments. The five Mn treatments were established in factorial combination with: 1, 7.5, and 20 mM Ca, 1, 5, and 15 mM Mg, 20 mM Na, 0, 2, and 10 \(\mu\)M Al, and two \(H^+\) activities (6.3 and 32 \(\mu\)M, corresponding to pH 5.2 and 4.5). These concentrations of Ca, Mg, Na, Al, and H are known to be non-toxic, reducing the growth of cowpea roots by <10% (Kopittke et al., 2011). Indeed, the ionic strengths (osmolarities) used here are known to be substantially lower than those which reduce the growth of cowpea roots (Kopittke et al., 2011). It is important to note that Al was used as an ameliorant rather than as a toxicant (i.e. Al is added at levels which, although non-toxic, may have substantial impacts upon the effects of toxicants due to changes in \(\psi_0\)). Therefore, differences in growth between these treatments are not due to toxicities of these cations, but rather due to other effects (such as excess Mn). There were two replicates of the 60 treatments giving a total of 120 experimental units.

Experiment 2 investigated the effects of cations (Ca, Mg, Na, H, and Al, at the same concentrations used in Experiment 1) at five Mn concentrations (0.05, 0.25, 1, 2.5, or 10 \(\mu\)M) considered adequate for root growth in longer term experiments. As for Experiment 1, there was a total of 60 treatments with two replicates.

All solutions contained 5 \(\mu\)M B as H\(_3\)BO\(_3\) which must be supplied continuously in the rooting medium (Brown and Shelp, 1997) and Ca at a concentration estimated to result in a minimum of 2.0 mM. \(\{\text{Ca}\}_0\) to ensure growth was not limited by Ca deficiency (Kopittke et al., 2011). Chloride salts were used for all treatments. Solution pH was not adjusted in any treatment other than those investigating \(H^+\) for which 0.1 M HCl was used to lower pH where necessary (all solutions with Al added were at pH 4.5). Solution pH was measured at both 0 h and 48 h. The calculated osmolarity of all solutions was <55 mOsm, and all rates of Ca, Mg, Na, H, and Al affected root growth by <10% (Kopittke et al., 2011). Solutions were collected upon completion of the experiment (48 h), acidified using concentrated HCl (32%, 10 M), and refrigerated at 4 °C prior to analysis by inductively coupled plasma mass spectroscopy (ICP-MS) for Mn.

The activities of metal ions in the bulk solution were calculated using PhreeqC 2.17 (Parkhurst, 2010) with the Minteq database. Final calculations of \(\psi_0\) were performed using the Gouy–Chapman–Stern (GCS) model (computer program provided by Dr TB Kinraide, USDA) with the average of the measured pH values in each treatment. The GCS program was modified to allow calculation of activity coefficients using the extended Debye–Hückel equation rather than the Davies equation (Lindsay, 1979). The GCS model combines electrostatic theory (Gouy–Chapman theory) with ion binding (Stern model) so that \(\psi_0\) can be computed (Tatulian, 1999; Kinraide and Wang, 2010). This model incorporates the intrinsic surface charge density \(\sigma_0\) of a membrane, the ion composition of the bathing medium, and ion binding to the membrane. Knowledge of \(\psi_0\) enables the calculation of ion activities at the PM exterior surface. The activity of ion \(I^\circ\) at the PM exterior surface \((\{I^\circ\}_b)\) is computed from the activity of \(I^\circ\) in the bulk-phase medium \((\{I^\circ\}_b)\) according to the Nernst equation, \(\{I^\circ\}_b = \{I^\circ\}_b \exp[-ZF\psi_0/(RT)]\), where \(Z\), \(F\), \(R\), and \(T\) are the charge on the ion, the Faraday constant, the gas constant, and temperature, respectively \((FRT/1257.7 = \psi_0\text{ is expressed in mV})\).

At harvest (i.e. immediately after photographing the roots after 48 h growth in the treatment solutions), the roots were rinsed briefly in 1 mM CaCl\(_2\) blotted dry and weighed, the replicates combined, placed into 50 ml conical flasks, and dried at 65 °C. Thereafter, 10 ml of 5:1 (v/v) nitric/perchloric acid was added. Following digestion, the samples were diluted to 10 ml using deionized water, and the concentration of Mn determined using ICP-MS.

The relative root elongation rate (RRER) and the Mn concentration in roots were analysed statistically using regression analysis, either by linear regression or Weibull equations of the general form

\[
RRER = b \exp \left[c(t)^d\right] 
\]

where \(b\) is the maximum growth rate in toxicant-free and Ca\(^{2+}\)-sufficient solutions \((b = 1\text{ when expressed as RRER})\), \(c\) is a strength coefficient which increases with the strength of the toxicant, \(T\) is...
Al and H in reducing the negativity of $\psi_0^0$ relative to those of Ca and Mg and especially that of Na.

It is possible to investigate the influence of changes in $\psi_0^0$ on {Mn$^{2+}$}$\mid_0$, and on the Nernst equation (Kinraide, 2006). With 1 mM Ca in solution, in which $\psi_0^0 = 35$ mV, {Mn$^{2+}$}$\mid_0$ would be 15 times higher than {Mn$^{2+}$}$\mid_b$. This is in marked contrast to a solution with 20 mM Ca ($\psi_0^0 = -2.9$ mV) in which {Mn$^{2+}$}$\mid_0$ would only be 1.3 times higher than {Mn$^{2+}$}$\mid_b$. The addition of 20 mM Na to a solution with 1.5 mM Ca has a much smaller influence on {Mn$^{2+}$}$\mid_0$ (see above), with {Mn$^{2+}$}$\mid_0$ being 10 times higher than {Mn$^{2+}$}$\mid_b$ at 0 mM Na ($\psi_0^0 = -30$ mV) compared with 7.1 times higher at 20 mM Na ($\psi_0^0 = -25$ mV).

### Root growth

In the absence of Mn stress, there was good root growth during the 48 h experimental period in both experiments (see Supplementary Tables S1 and S2 at JXB online). In Experiment 1, the mean (± standard deviation) RER was 1.3±0.1 mm h$^{-1}$ in the 12 treatments which contained a nominal concentration of 1 μM Mn, irrespective of differences in pH and concentrations of Ca, Mg, Na, or Al in solution. Concentrations of Mn in solution considered adequate for plant growth were studied in Experiment 2, and there were no significant effects of Mn on root growth over the range in treatments imposed (RER=1.3±0.1 mm h$^{-1}$, n=60).

A concentration of c. ≥250 μM Mn reduced root growth substantially with 1 mM Ca in solution in Experiment 1 (see Supplementary Table S1 at JXB online). Although the addition of up to 20 mM Ca, 15 mM Mg, 20 mM Na, 32 μM H$^+$, or 10 μM Al in the absence of high Mn reduced growth by <10%, their addition had a marked influence on growth in the Mn-toxic treatments. At pH 5.2, for example, 670 μM {Mn$^{2+}$}$\mid_b$ at 1 mM Ca resulted in a 55% reduction in root growth; 630 μM {Mn$^{2+}$}$\mid_b$ reduced RER by only 18% at 20 mM Ca. Overall, there was a clear distinction between the response in root growth to Mn in solution with 1 mM and 7.5 or 20 mM Ca in solution (Fig. 1A). There was a poor relationship between RER and {Mn$^{2+}$}$\mid_b$ (R$^2$=0.686) when combining all the data (Table 1). This was in marked contrast to the good relationship (R$^2$=0.892) between RER and {Mn$^{2+}$}$\mid_b$ (Fig. 1B; Table 1), suggesting Mn toxicity is a function Mn$^{2+}$ activity at the outer surface of the PM irrespective of Ca concentration in solution. A 50% reduction in root growth (EA50$^0_b$) of 2900 μM {Mn$^{2+}$}$\mid_0$ was calculated.

Evaluated separately, it is evident that additions of cations reduced the adverse effects of high Mn (≥250 μM) to varying degrees (see Supplementary Table S1 at JXB online). A concentration of 1 mM Mg in a solution containing 1 mM Ca alleviated the adverse effects of high Mn by ≥20% depending on the Mn concentration (230–1500 μM) in the bulk solution. It is difficult, however, to compare the effects of higher Mg concentrations because Ca was also increased to prevent Ca deficiency through low {Ca$^{2+}$}$\mid_0$. Nevertheless, the highest Mg level (15 mM) almost
completely overcame the adverse effect of high Mn on root growth. Decreasing solution pH from 5.2 to 4.5 (i.e., increasing the activity of $H^+$ from 6.3 $\mu$M to 32 $\mu$M) similarly alleviated the toxic effects of Mn on root growth by 21–45% depending on the Mn concentration in solution. By contrast, 20 mM Na in solution had, at best, a modest alleviating effect of 12–33%. Interestingly, whilst the addition of 2 $\mu$M Al alleviated Mn toxicity, root growth was slightly worse at 10 $\mu$M Al.

Combining all the treatments from Experiment 1 provides a more comprehensive comparison of the alleviatory effects of the various cations. As evident with Ca alone (Fig. 1A), a more comprehensive comparison of the alleviatory effects was slightly worse at 10 $\mu$M Al and the alleviation of Mn toxicity is non-specific and results from changes in $\{Mn^{2+}\}$ (which is influenced by the negativity of $\psi_0^b$). Using the appropriate regression (Table 1), the EA50 of Mn was calculated as 3300 $\mu$M $\{Mn^{2+}\}_0$, similar to the value of 2900 $\{Mn^{2+}\}_0$ calculated for Ca alone (Fig. 1B).

Besides the importance of $\{Mn^{2+}\}_0$, consideration should be given to $E_m$ with its influence on ion transport across the PM (Kinraide, 2001; Wang et al., 2011). The incorporation of an additional term besides $\{Mn^{2+}\}_0$ to account for the influence of $\psi_0^b$ on $E_m$ (equation 3) improved the relationship further ($R^2$=0.846; Fig. 2C). The positive value for $m_1$, 0.0183, suggests that at any given value for $\{Mn^{2+}\}_0$, a decrease in the negativity of $\psi_0^b$ (i.e., an increase in the electrical driving force for ion transport across the PM) decreases root growth (Table 1Table 1; Fig. 2C). This suggests that an increase in the electrical driving force for ion transport across the PM increases the toxic effect of Mn$^{2+}$.

### Mn concentrations in the root

As expected, the concentration of Mn in the root tissue increased with increase in $\{Mn^{2+}\}_0$, but the magnitude was greatly influenced both by the addition of other cations and their concentration (see Supplementary Tables S1 and S2 at JXB online). In Experiment 1, for example, the root tissue had a Mn concentration of 400 $\mu$g g$^{-1}$ at 670 $\mu$M $\{Mn^{2+}\}_0$ with 1 mM Ca, but only 150 $\mu$g g$^{-1}$ at 630 $\mu$M $\{Mn^{2+}\}_0$ with 20 mM Ca (Fig. 3A). The addition of Mg and H also markedly decreased the Mn concentration in root tissue. The addition of 20 mM Na did not influence the tissue Mn concentration, finding similar to the effect of Na on root growth. Once again, there was a variable effect of Al on the tissue Mn concentration. In Experiment 1, the addition of up to 10 $\mu$M Al tended to increase root tissue Mn concentration, whilst the opposite tendency was evident in Experiment 2.

### Table 1. Coefficients calculated using SYSTAT for the for the relationships between relative root elongation rate (RRER) or the concentration of Mn (mg kg$^{-1}$, fresh mass basis) in the root tissue and the activity of Mn$^{2+}$ in the bulk solution, $\{Mn^{2+}\}_b$, activity of Mn$^{2+}$ at the outer surface of the PM (PM), $\{Mn^{2+}\}_s$, and the electrical potential, $\psi_0^b$, of the outer surface of the PM

<table>
<thead>
<tr>
<th>Equation</th>
<th>Data source</th>
<th>$b$ or $e$</th>
<th>$c$ ($c_d$)</th>
<th>$m$ ($m_d$)</th>
<th>$b$ or $m_1$</th>
<th>$d$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRER=$1/\exp[c{Mn^{2+}}_b]$</td>
<td>Fig. 1A</td>
<td>9.69 x $10^{-4}$</td>
<td>1.34</td>
<td>0.686</td>
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<tr>
<td>RRER=$1/\exp[c{Mn^{2+}}_s]$</td>
<td>Fig. 1B</td>
<td>2.47 x $10^{-4}$</td>
<td>1.03</td>
<td>0.892</td>
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<tr>
<td>RRER=$1/\exp[c{Mn^{2+}}_s]$</td>
<td>Fig. 2A</td>
<td>8.17 x $10^{-4}$</td>
<td>1.40</td>
<td>0.673</td>
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<td></td>
<td></td>
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<tr>
<td>RRER=$m{Mn^{2+}}_b+1$</td>
<td>Fig. 2B</td>
<td>$-1.57x10^{-4}$</td>
<td>0.812</td>
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<tr>
<td>RRER=$m{Mn^{2+}}_b+1$</td>
<td>Fig. 2C</td>
<td>$-2.47x10^{-4}$</td>
<td>0.0183</td>
<td>0.846</td>
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<tr>
<td>Tissue=$m{Mn^{2+}}_s+e$</td>
<td>Fig. 3A</td>
<td>$-5.41$</td>
<td>0.439</td>
<td>0.790</td>
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<tr>
<td>Tissue=$m{Mn^{2+}}_s+e$</td>
<td>Fig. 3B</td>
<td>27.2</td>
<td>0.101</td>
<td>0.907</td>
<td></td>
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<tr>
<td>Tissue=$m{Mn^{2+}}_s+e$</td>
<td>Fig. 4A</td>
<td>0.540</td>
<td>0.356</td>
<td>0.769</td>
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<tr>
<td>Tissue=$m{Mn^{2+}}_s+e$</td>
<td>Fig. 4B</td>
<td>13.4</td>
<td>0.102</td>
<td>0.871</td>
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<tr>
<td>Tissue=$m{Mn^{2+}}_s+e$</td>
<td>Fig. 4C</td>
<td>$-0.765$</td>
<td>1.73</td>
<td>2.06</td>
<td>0.926</td>
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<tr>
<td>Tissue=$10^{-b/\exp[c{Mn^{2+}}_b]}$</td>
<td>Fig. 4D</td>
<td>9.05</td>
<td>0.251</td>
<td>5.13</td>
<td>0.590</td>
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<tr>
<td>Tissue=$10^{-b/\exp[c{Mn^{2+}}_s]}$</td>
<td>Fig. 4E</td>
<td>9.10</td>
<td>0.209</td>
<td>6.37</td>
<td>0.812</td>
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<tr>
<td>Tissue=$10^{-b/\exp[c{Mn^{2+}}_s]}$</td>
<td>Fig. 4F</td>
<td>9.02</td>
<td>0.222</td>
<td>0.00163</td>
<td>7.37</td>
<td>0.826</td>
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</table>
When the data were combined across all cations, highly significant relationships were obtained between root tissue Mn concentration and $[\text{Mn}^{2+}]_b$ in Experiment 1 (Fig. 4A) and Experiment 2 (Fig. 4D). As with root growth, the relationship improved with tissue Mn concentration related to $[\text{Mn}^{2+}]_0$ (Fig. 4B, E). Indeed, the $R^2$ value improved from 0.769 to 0.871 in Experiment 1, and from 0.590 to 0.791 in Experiment 2 (Table 1). These results suggest that the addition of cations influences the availability of Mn due to changes in $\psi_0$ and the consequent effect on $[\text{Mn}^{2+}]_0$. Furthermore, the incorporation of an additional term to account for the influence of $\psi_0$ on $E_{\text{ms, surf}}$ resulted in improvement, $R^2$ increasing to 0.926 in Experiment 1 and 0.826 in Experiment 2 (Fig. 4C, F). In both experiments, the values of $c_{i/m_1}$ were positive, suggesting that at any given value of $[\text{Mn}^{2+}]_0$, a decrease in the negativity of $\psi_0$ (i.e. an increase in the electrical driving force for ion transport across the PM) increases root tissue concentration of Mn (Table 1; Fig. 4C, F).

Despite the large difference in the nominal Mn concentration in Experiment 1 (1–1500 $\mu$M) and Experiment 2 (0.05–10 $\mu$M), root tissue Mn was closely and linearly related to $[\text{Mn}^{2+}]_0$ ($R^2 = 0.958$, $n = 120$) (combined data plotted on a log–log scale due to the wide range of values). There was further improvement ($R^2 = 0.970$) when both $[\text{Mn}^{2+}]_0$ and $E_{\text{ms, surf}}$ were considered (equation 4).

$$\log(1000Tissue) = 1000 - 997/\exp\left[\left(0.0160[1 + 0.00244\psi_0]\log\left[1000[\text{Mn}^{2+}]_0\right]\right)^{2.57}\right]$$

This allows a good prediction of cowpea root tissue Mn concentration which ranged from 0.71 to 570 $\mu$g g$^{-1}$ across solutions containing a $1\times10^5$ range in Mn measured in solution and considerable variation in concentrations of Ca, Mg, Na, or Al and in solution pH which resulted in changes of 0.027–4500 $\mu$M $[\text{Mn}^{2+}]_0$ (see Supplementary Fig. S1 at JXB online).

Discussion

This study demonstrates the importance of PM electrical properties, and in particular the negativity of $\psi_0$, in influencing plant–Mn interactions in cowpea. For plants grown in solutions containing toxic levels of Mn (Experiment 1), both root elongation and root tissue Mn concentration were more closely related to $[\text{Mn}^{2+}]_0$ than to $[\text{Mn}^{2+}]_b$ (Figs 2A, B, 4A, B). Similarly, root tissue Mn concentration was more closely related to $[\text{Mn}^{2+}]_0$ than to $[\text{Mn}^{2+}]_b$ for plants grown in solutions containing Mn at lower levels relevant for plant nutrition (Experiment 2) (Fig.
The data also suggest that $\psi_0$ has a second role in influencing plant–Mn interactions. Specifically, changes in the electrical driving force for ion transport across the PM ($E_{m, surf}$) influence (i) root elongation in Mn-toxic solutions (Fig. 2C) and (ii) tissue Mn concentrations in both Mn-sufficient and Mn-toxic solutions (Fig. 4C, F). In the current study, calculated values of $\psi_0$ have been used as a surrogate for $E_{m, surf}$; a decrease in the negativity of $\psi_0$ increases $E_{m, surf}$ and thus increases the electrical driving force for Mn transport across the PM (Kinraide, 2001; Wang et al., 2011). Overall, this indicates that changes in $\psi_0$ influence plant–Mn interactions through two mechanisms which partially, although not entirely, offset each other. Specifically, the addition of cations decreases the negativity of $\psi_0$ which concomitantly (i) decreases $\{\text{Mn}^{2+}\}_o^0$ and (ii) increases the electrical driving force for transport of Mn across the PM ($E_{m, surf}$).

The incorporation of a term accounting for changes in $E_{m, surf}$ along with $\{\text{Mn}^{2+}\}_o^0$ improved relationships between root growth and Mn concentration in roots in all three instances (Figs 2C, 4C, F) suggesting that transport across the PM is required for Mn to exert its toxic effect. Compared with other trace metals such as Al and Cu, Mn is readily transported to the shoots (Foy, 1984). This observation regarding the importance of $E_{m, surf}$ for Mn is in contrast to that observed for Cu$^{2+}$ (PM Kopittke, TB Kinraide, P Wang, FPC Blamey, SM Reichman, and NW Menzies, unpublished data). Both Al and Cu bind more
strongly to the cell wall, but further investigation is required to determine if the difference between toxicities of these two trace metals and that of Mn reflects different sites of action. The results of the current study regarding the importance of $\psi'_0$ are emphasized by the re-analysis of published data (Vlamis and Williams, 1962), which demonstrates the importance of $\{\text{Mn}^{2+}\}_{0}$ for plant nutrition (see Supplementary Fig. S2 at JXB online). In the present study, the magnitude of the effect of the various cations on plant–Mn interactions conforms to that which is expected from their effectiveness at reducing the negativity of $\psi'_0$ ($\text{Al}^{3+}>\text{H}^+>\text{Ca}^{2+}\approx\text{Mg}^{2+}>\text{Na}^+$) (Kinraide, 2006; Wang et al., 2008). The addition of comparatively low levels of $\text{H}^+$ (up to 32 $\mu$M) or high concentrations of Ca (20 mM) or Mg (15 mM) substantially reduced the negativity of $\psi'_0$ thereby reducing Mn uptake and its consequent toxicity; high concentrations of Na (20 mM) had no marked effect. The results regarding Al were unexpected given that the non-toxic concentrations used ($\leq 10$ $\mu$M) decreased the negativity of $\psi'_0$ by c. 10 mV (see Supplementary Tables S1 and S2 at JXB online). This was expected to reduce tissue Mn and its toxicity, but the effects of Al on root growth and tissue Mn concentration was variable (Figs 2A, 4A, D). This is in contrast to that reported for Cu using the same experimental system, in which $10$ $\mu$M Al consistently reduced the toxicity of Cu (PM Kopittke, TB Kinraide, P Wang, FPC Blamey, SM Reichman, and NW Menzies, unpublished data). The reason for these observations regarding Al is unclear, although it is possible that there is an antagonistic effect between Al and Mn (Taylor et al., 1998). Indeed, Al is highly rhizotoxic, and levels slightly higher than those used in the current experiment are known to reduce root growth.

Although alleviation of Mn toxicity was found to be non-specific in the current study, this does not preclude specific effects in other instances. Several studies have demonstrated that the addition of cations may alleviate toxicities to an extent greater than predicted from electrostatic effects. For instance, Pedler et al. (2004) reported that 1–5 $\mu$M Mg alleviates Zn toxicity in wheat ($\text{Triticum aestivum}$ L.), concentrations that are too low to influence the activity of Zn$^{2+}$ at the PM surface. Similarly, Kopittke et al. (2011) reported that 200–700 $\mu$M K alleviates Na toxicity in cowpea, and Silva et al. (2001) reported that 25–50 $\mu$M Mg alleviated Al toxicity in soybean ($\text{Glycine max}$ L. Merr.). In some (but not all) instances, these ‘specific’ effects occur when the two cations have similar ionic radii. For example, the hydrated ionic radius of Zn$^{2+}$ is 0.430 nm whilst that of Mg$^{2+}$ is 0.428 nm (Volkov et al., 1997).

The $\{\text{Mn}^{2+}\}_{b}$ causing a 50% reduction in root growth (E50b) in the current study (c. 500 to >1000 $\mu$M; Fig. 2A) is substantially higher than that found in some other studies. In a meta-analysis of solution culture studies, Kopittke et al. (2010) reported that the 25th and 75th percentiles for the toxic concentration of Mn were 5 $\mu$M and 180 $\mu$M. Analysis of data presented by Edwards and Asher (1982) showed that the Mn concentration causing a 50% reduction for whole plant growth of cowpea was c. 4 $\mu$M Mn. This apparent discrepancy most likely arises from the short-term nature of the current study (48 h), compared with the average length of 17 d for the studies reported by Kopittke et al. (2010) and the 18–31 d of Edwards and Asher (1982). Indeed, for field-grown plants (full life cycle), the toxic effects of Mn are manifest predominantly in the shoots (Nable and Loneragan, 1984), requiring an extended period for Mn accumulation. Regardless, the current study demonstrates the importance of PM electrostatic effects in both the short-term nutrition and toxicity of Mn, with further studies required to examine longer-term effects.

Conclusions

This study demonstrated that short-term root–Mn interactions were related to the electrical properties of the PM in cowpea. For plants grown in solutions containing toxic levels of Mn, both root elongation and root tissue Mn concentration were more closely correlated to $\{\text{Mn}^{2+}\}_{0}$ than to $\{\text{Mn}^{2+}\}_{b}$. Similarly, root tissue Mn concentration was more closely related to $\{\text{Mn}^{2+}\}_{0}$ than to $\{\text{Mn}^{2+}\}_{b}$ for plants grown at levels of Mn relevant for plant nutrition. Changes in the electrical driving force for ion transport across the PM ($E_{\text{m,surf}}$) also influenced both root elongation and Mn concentration in roots. These results demonstrate that, for cowpea, the alleviation of Mn toxicity by cations such as Ca and Mg is non-specific and results from a reduction in the negativity of $\psi'_0$. Although the data do not preclude specific effects (such as competition), the data demonstrate the importance of PM electrostatic effects in both the nutrition and toxicity of Mn. Research is needed, however, to establish whether or not the findings have implications for plant Mn status in the longer term.

Supplementary data

Supplementary data can be found at JXB online.

Supplementary Table S1. Composition of solutions used in Experiment 1.

Supplementary Table S2. Composition of solutions used in Experiment 2.

Supplementary Fig. S1. Comparison of measured and predicted concentrations of Mn in root tissue for Experiments 1 and 2.

Supplementary Fig. S2. Re-analysis of the data of Vlamis and Williams (1962).

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