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Electronic Supplementary Information (ESI) for Metallomics.

Evaluating effects of iron on manganese toxicity in soybean and sunflower using synchrotron-based X-ray fluorescence microscopy and X-ray absorption spectroscopy

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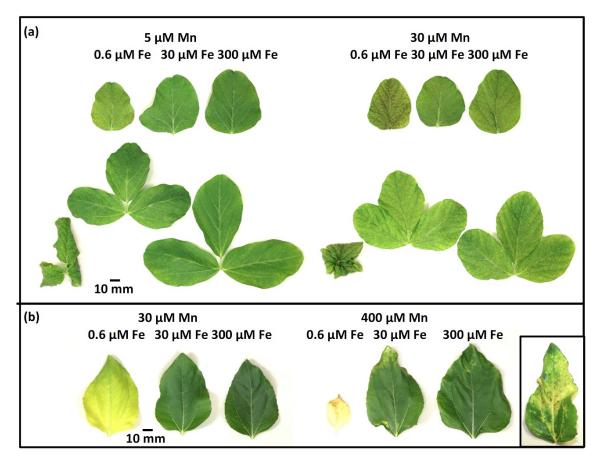
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† Electronic supplementary information (ESI) available. See DOI:

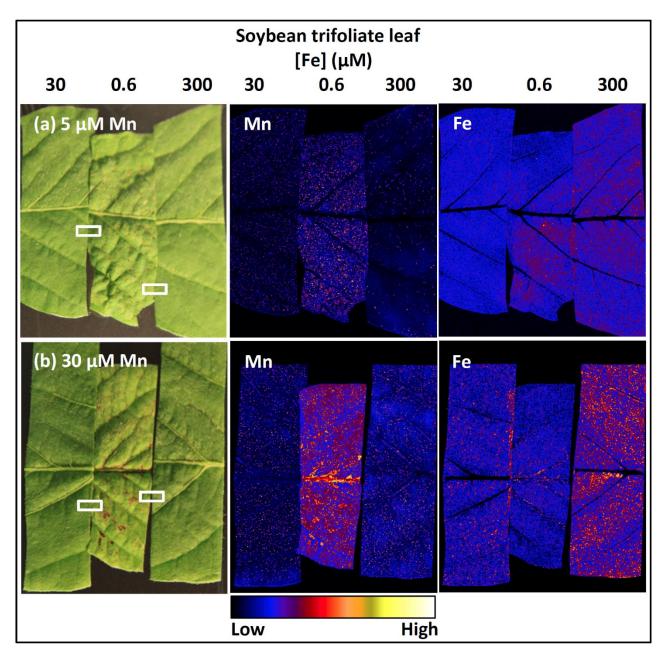
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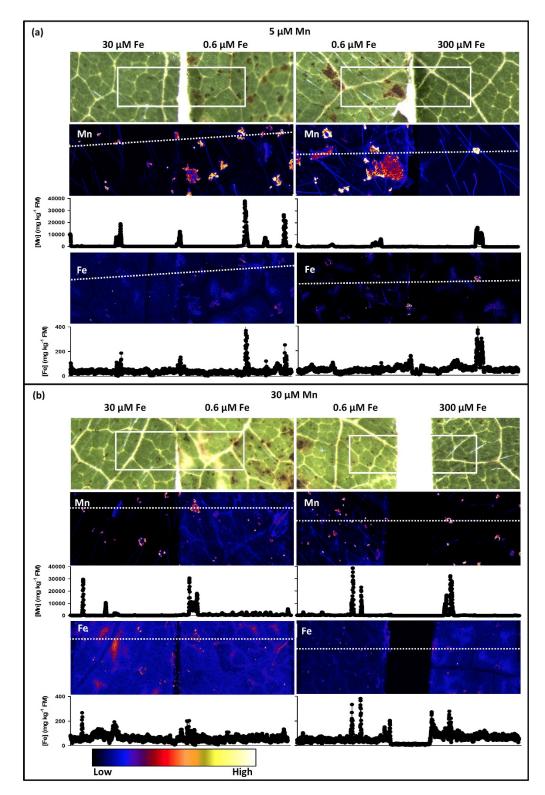
## **Supplementary Information**



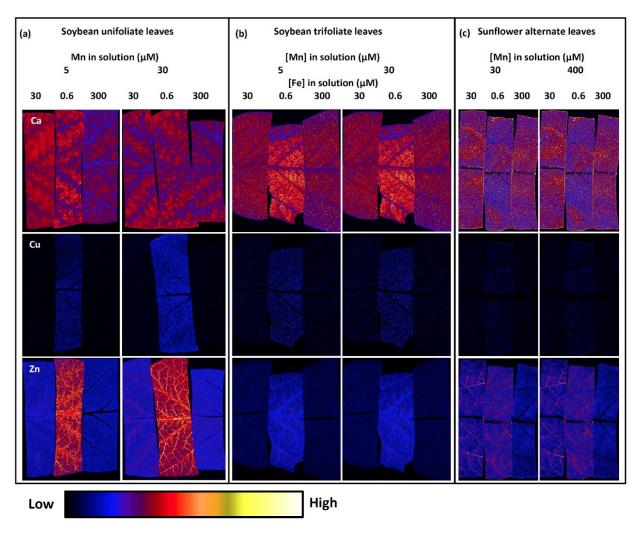
**Supplementary Fig. S1** Visible effects of Mn and Fe in solution on soybean and sunflower leaves. (a) Unifoliate and trifoliate leaves of soybean grown for 1 week at 5 and 30  $\mu$ M Mn with 0.6, 30, and 300  $\mu$ M Fe (Experiment 2). (b) Lower alternate leaves of sunflower grown at 30 and 400  $\mu$ M Mn with 0.6, 30, and 300  $\mu$ M Fe. Insert: Unpublished image from the study of Blamey et al. (2018a) showing the chlorosis and distortion of a lower alternate leaf of sunflower grown at 400  $\mu$ M Mn and 6  $\mu$ M Fe.



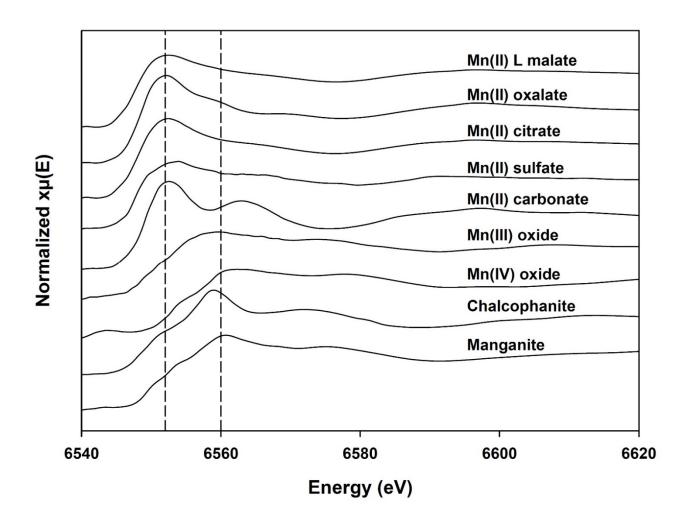
**Supplementary Fig. S2** Optical images and  $\mu$ -XRF survey scans of Mn and Fe distributions in trifoliate leaf sections of soybean grown for 1 week in solutions with (a) 5 and (b) 30  $\mu$ M Mn and with 30, 0.6, and 300  $\mu$ M Fe in solution (Experiment 2). The white boxes in the optical images indicate the locations of the 3.05 mm  $\times$  1.00 mm  $\mu$ -XRF detailed scans and the color scale in (b) applies to all Mn and Fe distributions.



**Supplementary Fig. S3** Optical images and  $\mu$ -XRF detailed scans (3.05 mm  $\times$  1.00 mm) of Mn and Fe distributions in trifoliate leaf sections of soybean grown at (a) 5 and (b) 30  $\mu$ M Mn with 30, 0.6, and 300  $\mu$ M Fe in solution (Experiment 2). The dotted white lines indicate transects along which the Mn and Fe concentrations were determined. Valid comparisons may be made between Fe treatments within each image. The color scale in (b) applies to all Mn and Fe  $\mu$ -XRF scans.



Supplementary Fig. S4  $\mu$ -XRF survey scans of Ca, Cu, and Zn distributions and concentrations in sections of (a) soybean unifoliate leaves, (b) soybean trifoliate leaves, and (c) sunflower lower alternate leaves after 1 week's growth in complete nutrient solutions with two Mn treatments and three Fe treatments (Experiment 2). The color scale applies to all images.



**Supplementary Fig. S5** Normalized K-edge XANES spectra of nine Mn compounds showing differences over the range from 6540 to 6620 eV. The vertical dashed lines correspond approximately to the white-line peak of Mn(II) at 6,552 eV and that of Mn(III) and Mn(IV) at 6,560 eV.

**Supplementary Table S1** Main effects and interactions of Mn and Fe in solution on concentrations of nine selected nutrients in soybean unifoliate leaves on a dry mass (DM) basis. A value of 19.5 % DM may be used to convert concentrations to a fresh mass basis. (Experiment 1)

Final in Market (1)   Fig.	[Mn] in unifoliate	leaves (mg kg-1)	Т	Fe means		
Fe  in solution	[Mn] in unifoliate leaves (mg kg <sup>-1</sup> )		[Mn] in solution (µM)			Te means
Fe  in solution   (μM)   300   240 ± 40   220 ± 10   820 ± 40   520 ± 70   500   60   Mn means   250 ± 20   430 ± 90   1700 ± 230   120 ± 140   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   50 ± 10   160 ± 10   160 ± 10   50 ± 10   160 ± 10	IVIII I'C IVIII^I			-		2010 ± 220
(μM)         300         280±40         220±10         800±40         530±60           (Fe] in unifoliate leaves (mg kg¹)         (Mn] in solution (μM)         Femeans           Mn** Fe**Mn×Fe**         0.5         5         30           (μN)         30         1260±200         150±20         360±70         530±10           (μN)         30         1260±200         150±20         360±70         530±10           (μN)         Mm means         900±160         170±30         310±50         420±60           (Cu] in unifoliate leaves (mg kg¹)         [Mn] in solution (μM)         Femeans           (EPe] in solution         30         11.7±1.3         6.2±0.2         10.9±1.1         9.9±0.8           (IpH)         300         11.7±2.9         9.0±1.0         10.0±0.1         15.3±1.1           (Era) in unifoliate leaves (mg kg¹)         [Mn] in solution (μM)         Fe means           Mn NS Fe*Mn×Fe*Mn×Fe** <td rowspan="3"></td> <td></td> <td></td> <td></td> <td></td> <td></td>						
Mn means						
$ \begin{array}{ c c c c c }\hline [Fe] & in unifoliate leaves (mg kg^{-1}) & [Mn] & in solution (\mu M) \\ \hline Mn^{++} Fe^{++} Mn^{\times} Fe^{++} & 0.6 & 0.5 & 5 & 30 \\ \hline (Fe] & in solution & 0.6 & 90 & + 10 & 100 & + 10 & 50 & + 0 & 70 & \pm 10 \\ \hline (Fe] & in solution & 30 & 1260 & \pm 200 & 150 & \pm 20 & 360 & \pm 70 & 530 & \pm 10 \\ \hline (\mu M) & 300 & 1340 & \pm 170 & 250 & \pm 60 & 510 & \pm 100 & \pm 100 \\ \hline Mn means & 900 & \pm 160 & 170 & \pm 30 & 310 & \pm 50 & 420 & \pm 60 \\ \hline (Cu] & in unifoliate leaves (mg kg^{-1}) & [Mn] & in solution (\mu M) & Fe means \\ \hline (Fe] & in solution & 30 & 11.7 & \pm 1.3 & 6.2 & \pm 0.2 & 10.9 & \pm 1.1 & 9.9 & \pm 0.8 \\ \hline (\mu M) & 300 & 11.7 & \pm 1.3 & 6.2 & \pm 0.2 & 10.9 & \pm 1.1 & 9.9 & \pm 0.8 \\ \hline (\mu M) & 300 & 14.0 & \pm 0.9 & 7.3 & \pm 0.7 & 9.2 & \pm 0.6 & 9.9 & \pm 0.7 \\ \hline (\mu M) & 300 & 14.0 & \pm 0.9 & 7.3 & \pm 0.7 & 9.2 & \pm 0.6 & 9.9 & \pm 0.7 \\ \hline (\mu M) & 300 & 14.0 & \pm 0.9 & 7.3 & \pm 0.7 & 9.2 & \pm 0.6 & 9.9 & \pm 0.7 \\ \hline (\mu M) & 300 & 14.0 & \pm 0.9 & 7.3 & \pm 0.7 & 9.2 & \pm 0.6 & 9.9 & \pm 0.7 \\ \hline (Fe] & in solution & 30 & 170 & \pm 20 & 90 & \pm 10 & 160 & \pm 20 & 390 & \pm 20 \\ \hline (Fe] & in solution & 30 & 170 & \pm 20 & 90 & \pm 10 & 160 & \pm 20 & 150 & \pm 10 \\ \hline (\mu M) & 300 & 200 & \pm 20 & 80 & \pm 10 & 140 & \pm 20 & 140 & \pm 10 \\ \hline (\mu M) & 300 & 200 & \pm 20 & 80 & \pm 10 & 140 & \pm 20 & 140 & \pm 10 \\ \hline (Fe] & in solution & 30 & 170 & \pm 20 & 90 & \pm 10 & 160 & \pm 20 & 150 & \pm 10 \\ \hline (Mn) & 300 & 200 & 20 & 80 & \pm 10 & 140 & \pm 20 & 140 & \pm 10 \\ \hline (Fe] & in solution & 30 & 282 & \pm 0.11 & 3.02 & \pm 0.11 & 3.02 & \pm 0.10 \\ \hline (Fe] & in solution & 30 & 282 & \pm 0.07 & 3.02 & \pm 0.2 & 2.70 & \pm 0.06 & 2.81 & \pm 0.07 \\ \hline (MR) & 300 & 282 & \pm 0.07 & 3.02 & \pm 0.22 & 2.70 & \pm 0.06 & 2.81 & \pm 0.07 \\ \hline (MR) & 300 & 282 & \pm 0.07 & 3.02 & \pm 0.22 & 2.70 & \pm 0.06 & 2.81 & \pm 0.07 \\ \hline (Fe] & in solution & 30 & 2.82 & \pm 0.07 & 3.02 & \pm 0.22 & 2.70 & \pm 0.06 & 2.81 & \pm 0.07 \\ \hline (Fe] & in solution & 30 & 3.03 & \pm 0.01 & 0.34 & \pm 0.02 & 0.33 & \pm 0.02 \\ \hline (Fe] & in solution & 30 & 0.40 & \pm 0.00 & 0.42 & \pm 0.03 & 0.44 & \pm 0.02 & 0.33 & \pm 0.02 \\ \hline (Fe] & in solution & 30 & 1.88 & \pm 0.13 & 1.92 & \pm 0.14 &$						
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	[Ea] in unifoliate 1					
$ \begin{bmatrix} \text{Fe} \mid \text{in solution} \\ \text{(}\mu\text{M}) \\ \text{300} \\ \text{300} \\ \text{3000} \\ \text{3300} \\ \text{340} \\ \text{340} \\ \text{40} \\ 4$						remeans
$ [Fe] \ in \ solution \ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $	IVIII - I e - IVIII - I			· ·		70 ± 10
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Fe] in solution					
Mn means						
	(μινι)					
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Cu] in unifoliate					
$ \begin{bmatrix} \text{[Fe] in solution} \\ (\mu\text{M}) & 300 & 11.7 \pm 1.3 & 6.2 \pm 0.2 & 10.9 \pm 1.1 \\ 300 & 11.7 \pm 1.3 & 6.2 \pm 0.2 & 10.9 \pm 1.1 \\ 300 & 14.0 \pm 0.9 & 7.3 \pm 0.7 & 9.2 \pm 0.6 & 9.9 \pm 0.7 \\ Mn  \text{means} & 16.9 \pm 1.9 & 11.3 \pm 1.8 & 16.4 \pm 1.7 & 15.3 \pm 1.1 \\ \hline{[Zn] in unifoliate leaves (mg kg^+) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ 0.6 & 35.0 \pm 40 & 40.0 \pm 70 & 42.0 \pm 20 & 390 \pm 20 \\ \hline{[Fe] in solution} & 30 & 17.0 \pm 20 & 90 \pm 10 & 160 \pm 20 & 15.0 \pm 10 \\ Mn  \text{means} & 24.0 \pm 20 & 190 \pm 40 & 24.0 \pm 20 & 230 \pm 20 \\ \hline{[Ca] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ 0.6 & 31.4 \pm 0.21 & 3.13 \pm 0.11 & 3.07 \pm 0.17 & 3.10 \pm 0.10 \\ \hline{[Fe] in solution} & 30 & 2.82 \pm 0.07 & 3.02 \pm 0.22 & 2.70 \pm 0.06 & 2.81 \pm 0.07 \\ Mn  \text{NS Fe NS Mn} \times \text{Fe NS} & 0.5 & 5 & 30 \\ 0.6 & 3.14 \pm 0.21 & 3.13 \pm 0.11 & 3.07 \pm 0.17 & 3.10 \pm 0.10 \\ \hline{[Fe] in solution} & 30 & 2.82 \pm 0.07 & 3.02 \pm 0.22 & 2.70 \pm 0.06 & 2.81 \pm 0.07 \\ Mn  \text{means} & 2.93 \pm 0.09 & 3.06 \pm 0.03 & 2.95 \pm 0.07 & 2.97 \pm 0.05 \\ \hline{[Mg] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ Mn^** Fe^** Mn \times Fe^{**} & 0.5 & 5 & 30 \\ \hline{[Mg] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ 0.6 & 0.38 \pm 0.04 & 0.42 \pm 0.03 & 0.48 \pm 0.03 & 0.44 \pm 0.02 \\ \hline{[Fe] in solution} & 30 & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.33 \pm 0.02 \\ \hline{[Mg] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ Mn^** Fe^** Mn \times Fe^{**} & 0.5 & 5 & 30 \\ \hline{[Mg] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ Mn^** Fe  NS  Mn \times Fe^* & 0.5 & 5 & 30 \\ \hline{[Fe] in solution} & 30 & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.33 \pm 0.02 & 0.33 \pm 0.02 \\ \hline{[K] in unifoliate leaves (%) & [Mn] in solution (\mu\text{M}) & Fe  \text{means} \\ Mn^** Fe  NS  Mn \times Fe^* & 0.5 & 5 & 30 \\ \hline{[Fe] in solution} & 30 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline{[Fe] in solution} & 30 & 1.99 \pm 0.01 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline{[Fe] in solution} & 30 & 1.99 \pm 0.01 & 1.43 \pm 0.00 & 0.12 \pm 0.01 & 0.13 \pm 0.01 \\ \hline{[Fe] in solution} & 30 & 0.10 \pm 0.01 & 0.12 \pm 0.01$						Te means
$ [Fe] \text{ in solution} \\ (\mu\text{M}) \\ \hline \hline \\ 300 \\ \hline \\ (\mu\text{M}) \\ \hline \\ \hline \\ 300 \\ \hline \\ \hline \\ Mn \text{ means} \\ \hline \\ [A] 11.7 \pm 1.3 \\ \hline \\ 1.6.9 \pm 0.9 \\ \hline \\ Mole \\ \hline \\ Mn \text{ means} \\ \hline \\ [A] 11.3 \pm 1.8 \\ \hline \\ 16.9 \pm 1.9 \\ \hline \\ 11.3 \pm 1.8 \\ \hline \\ 16.9 \pm 1.9 \\ \hline \\ 11.3 \pm 1.8 \\ \hline \\ 16.4 \pm 1.7 \\ \hline \\ 15.3 \pm 1.1 \\ \hline \\ [A] 16.9 \pm 0.9 \\ \hline \\ [A] 16.9$	IVIII I'C IVIII^I			· ·		26.0 ± 1.7
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Fe] in solution					
$ \begin{array}{ c c c c c c } \hline & Mn  means \\ \hline [Zn]  in  unifoliate  leaves  (mg  kg^{-1}) \\ \hline Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ Mn  NS  Fe^{**}  Mn \times Fe  NS \\ \hline \\ (\mu M) \\ \hline \\ Mn  means \\ \hline \\ (\mu M) \\ \hline \\ Mn  means \\ \hline \\ (240 \pm 20) \\ \hline \\ Mn  means \\ \hline \\ (240 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (200 \pm 20) \\ \hline \\ (200 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 40) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (230 \pm 20) \\ \hline \\ (310 \pm 20) \\ \hline \\ (240 \pm 20) \\ \hline \\ (330 \pm 20, 10) \\ \hline \\ (310 \pm 20) \\ \hline \\ (310 \pm 20$						
$ \begin{array}{ c c c c c }\hline [Zn] & in unifoliate leaves (mg kg^{-1}) \\ Mn NS Fe^{**} Mn^{*}Fe NS \\ \hline \\ 0.6 \\ \hline \\ 170 \pm 20 \\ \hline \\ 180 \pm 2$	(μινι)					
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	[7n] in unifoliate 1					
$ [Fe] \ in \ solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $						Te means
$ [Fe] \ in \ solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $	WIII NO I'C WIII^					300 + 20
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Fe] in solution					
Mn means   240 ± 20   190 ± 40   240 ± 20   230 ± 20   [Ca] in unifoliate leaves (%)   [Mn] in solution (μM)   Fe means						
$ \begin{array}{ c c c c c }\hline [Ca] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) \\ Mn NS Fe NS & Mn \times Fe NS & 0.5 & 5 & 30 \\ \hline [Fe] & in solution & 0.6 & 3.14 \pm 0.21 & 3.13 \pm 0.11 & 3.07 \pm 0.17 & 3.10 \pm 0.10 \\ (\mu M) & 300 & 2.82 \pm 0.07 & 3.02 \pm 0.22 & 2.70 \pm 0.06 & 2.81 \pm 0.07 \\ Mn & means & 2.93 \pm 0.09 & 3.06 \pm 0.08 & 2.95 \pm 0.07 & 2.97 \pm 0.05 \\ \hline [Mg] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [M*] & Fe** Mn \times Fe** & 0.5 & 5 & 30 \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [K] & in unifoliate leaves (\%) & [Mn] & in solution (\mu M) & Fe means \\ \hline [Mn*Fe NS Mn \times Fe* & 0.5 & 5 & 30 \\ \hline [Fe] & in solution & 30 & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline [Mn] & 300 & 1.85 \pm 0.13 & 1.92 \pm 0.14 & 1.89 \pm 0.10 & 1.89 \pm 0.07 \\ \hline [Mn] & means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline [Mn] & in solution (\mu M) & Fe means \\ \hline [Mn*Fe** Mn \times Fe* & 0.5 & 5 & 30 \\ \hline [Fe] & in solution & 30 & 0.10 \pm 0.01 & 0.12 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [Mn] & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [Mn] & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [Mn] & in solution (\mu M) & Fe means \\ \hline [Fe] & in solution & 30 & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline [Fe] & in solution & 30 & 0.10 \pm 0.01 & 0.12 \pm 0.01 & 0.12 \pm 0.01 & 0.12 \pm 0.01 \\ \hline [Fe] & in solution & 30 & 0.10 \pm 0.01 & 0.22 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] & in solution & 30 & 0.10 \pm 0.01 & 0.22 \pm 0.01 & 0.23 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] & in solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] & in solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.2$	(μινι)					
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Cal in unifoliate 1					
$ [Fe] \ in \ solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $						Te means
$ [Fe] \  in \  solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $	WIII NO I'C NO WIII			· ·		3 10 + 0 10
$ \begin{array}{ c c c c c } \hline (\mu \dot{M}) & 300 & 2.82 \pm 0.07 & 3.02 \pm 0.22 & 2.70 \pm 0.06 & 2.81 \pm 0.07 \\ \hline Mn means & 2.93 \pm 0.09 & 3.06 \pm 0.08 & 2.95 \pm 0.07 & 2.97 \pm 0.05 \\ \hline [Mg] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn** Fe** Mn×Fe** & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.40 \pm 0.04 & 0.27 \pm 0.02 & 0.34 \pm 0.02 & 0.33 \pm 0.02 \\ \hline (\mu M) & 300 & 0.43 \pm 0.03 & 0.31 \pm 0.01 & 0.34 \pm 0.02 & 0.33 \pm 0.02 \\ \hline (Mn) \ in \ solution & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.33 \pm 0.02 & 0.38 \pm 0.01 \\ \hline [K] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn*Fe \ NS \ Mn×Fe* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 1.98 \pm 0.17 & 1.69 \pm 0.08 & 1.64 \pm 0.09 & 1.74 \pm 0.07 \\ \hline [Fe] \ in \ solution & 30 & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline [Mn] \ means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline [Fe] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn*Fe** Fe** Mn×Fe* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.12 \pm 0.01 & 0.22 \pm 0.02 & 0.25 \pm 0.02 & 0.21 \pm 0.02 \\ \hline [Fe] \ in \ solution & 30 & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline (\mu M) & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [S] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn*Fe** Mn×Fe** & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline [S] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn*Fe** Mn×Fe NS & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.10 \pm 0.01 & 0.22 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.2$	[Fe] in solution					
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$						
$ \begin{array}{ c c c c c }\hline [Mg] \ in \ unifoliate \ leaves (\%) \\ Mn**Fe**Mn\times Fe** & 0.5 & 5 & 30 \\ \hline \\ [Fe] \ in \ solution \\ (\mu M) & 300 & 0.40 \pm 0.04 & 0.27 \pm 0.02 & 0.34 \pm 0.02 & 0.33 \pm 0.02 \\ Mn \ means & 0.40 \pm 0.04 & 0.27 \pm 0.02 & 0.34 \pm 0.02 & 0.33 \pm 0.02 \\ Mn \ means & 0.40 \pm 0.03 & 0.31 \pm 0.01 & 0.34 \pm 0.02 & 0.36 \pm 0.01 \\ Mn \ means & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.39 \pm 0.02 & 0.38 \pm 0.01 \\ K] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ Mn*Fe \ NS \ Mn\times Fe* & 0.5 & 5 & 30 \\ [Fe] \ in \ solution & 30 & 1.98 \pm 0.17 & 1.69 \pm 0.08 & 1.64 \pm 0.09 & 1.74 \pm 0.07 \\ Mn \ means & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ Mn \ means & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ Mn \ means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ [Fe] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ Mn**Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ Mn \ means & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ Mn \ means & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ Mn \ means & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.16 \pm 0.01 \\ Mn \ means & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ Mn**Fe** \ Mn\times Fe \ NS & 0.5 $	(μινι)					
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	[Ma] in unifoliate					
$ [Fe] \ in \ solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $						
$ [Fe] \  in \  solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $	17111 1 17111 1					$0.44 \pm 0.02$
$ \begin{array}{ c c c c c } \hline (\mu M) & 300 & 0.43 \pm 0.03 & 0.31 \pm 0.01 & 0.34 \pm 0.02 & 0.36 \pm 0.01 \\ \hline Mn \ means & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.39 \pm 0.02 & 0.38 \pm 0.01 \\ \hline [K] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn^* \ Fe \ NS \ Mn^\times Fe^* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 1.99 \pm 0.17 & 1.69 \pm 0.08 & 1.64 \pm 0.09 & 1.74 \pm 0.07 \\ \hline [Fe] \ in \ solution & 30 & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline (\mu M) & 300 & 1.85 \pm 0.13 & 1.92 \pm 0.14 & 1.89 \pm 0.10 & 1.89 \pm 0.07 \\ \hline Mn \ means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline [P] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn^** \ Fe^{**} \ Mn^\times Fe^* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.12 \pm 0.01 & 0.22 \pm 0.02 & 0.25 \pm 0.02 & 0.21 \pm 0.02 \\ \hline [Fe] \ in \ solution & 30 & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline (\mu M) & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [S] \ in \ unifoliate \ leaves (%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn^** \ Fe^* \ Mn^\times Fe \ NS & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 0.6 & 0.20 \pm 0.01 & 0.25 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.25 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.00 & 0.22 \pm 0.01 & 0.21 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm$	[Fe] in solution					
$ \begin{array}{ c c c c c c c } \hline & Mn \ means & 0.40 \pm 0.02 & 0.33 \pm 0.02 & 0.39 \pm 0.02 & 0.38 \pm 0.01 \\ \hline [K] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn^* \ Fe \ NS \ Mn^\times Fe^* & 0.5 & 5 & 30 \\ \hline \\ [Fe] \ in \ solution & 30 & 1.98 \pm 0.17 & 1.69 \pm 0.08 & 1.64 \pm 0.09 & 1.74 \pm 0.07 \\ \hline [Fe] \ in \ solution & 30 & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline (\mu M) & 300 & 1.85 \pm 0.13 & 1.92 \pm 0.14 & 1.89 \pm 0.10 & 1.89 \pm 0.07 \\ \hline Mn \ means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline [P] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn^** \ Fe^{**} \ Mn^\times Fe^* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.12 \pm 0.01 & 0.22 \pm 0.02 & 0.25 \pm 0.02 & 0.21 \pm 0.02 \\ \hline [Fe] \ in \ solution & 30 & 0.11 \pm 0.00 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline (\mu M) & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [S] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline [S] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline [S] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline [Fe] \ in \ solution & 30 & 0.20 \pm 0.01 & 0.25 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 & 0.21 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.00 & 0.22 \pm 0.01 & 0.21 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline [Fe] \ in \ solution & 0.17 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.$						
$ \begin{array}{ c c c c c c }\hline [K] & \text{in unifoliate leaves} & (\%) \\ \hline Mn^* & \text{Fe NS Mn} \times \text{Fe} * \\ \hline \\ Mn^* & \text{Fe NS Mn} \times \text{Fe} * \\ \hline \\ & 0.6 \\ \hline \\ & 1.98 \pm 0.17 \\ \hline \\ & 1.69 \pm 0.08 \\ \hline \\ & 1.64 \pm 0.09 \\ \hline \\ & 1.64 \pm 0.09 \\ \hline \\ & 1.74 \pm 0.07 \\ \hline \\ & 1.85 \pm 0.07 \\ \hline \\ & 1.85 \pm 0.13 \\ \hline \\ & 1.92 \pm 0.14 \\ \hline \\ & 1.89 \pm 0.10 \\ \hline \\ & 1.89 \pm 0.10 \\ \hline \\ & 1.89 \pm 0.07 \\ \hline \\ & 1.85 \pm 0.03 \\ \hline \\ & 1.85 \pm 0.13 \\ \hline \\ & 1.92 \pm 0.14 \\ \hline \\ & 1.89 \pm 0.10 \\ \hline \\ & 1.89 \pm 0.07 \\ \hline \\ & 1.89 \pm 0.07 \\ \hline \\ & 1.84 \pm 0.05 \\ \hline \\ & 1.83 \pm 0.04 \\ \hline \\ & [P] & \text{in unifoliate leaves} (\%) \\ \hline & [Mn] & \text{in solution} (\mu M) \\ \hline & Mn^* & \text{Fe} * Mn \times \text{Fe} * \\ \hline & 0.5 \\ \hline & 5 \\ \hline & 30 \\ \hline \\ & [Fe] & \text{in solution} \\ \hline & 0.6 \\ \hline & 0.12 \pm 0.01 \\ \hline & 0.22 \pm 0.02 \\ \hline & 0.22 \pm 0.02 \\ \hline & 0.25 \pm 0.02 \\ \hline & 0.21 \pm 0.02 \\ \hline \\ & [Fe] & \text{in solution} \\ \hline & 0.6 \\ \hline & 0.11 \pm 0.00 \\ \hline & 0.16 \pm 0.01 \\ \hline & 0.13 \pm 0.01 \\ \hline & 0.17 \pm 0.01 \\ \hline & 0.17 \pm 0.01 \\ \hline \\ & 0.23 \pm 0.01 \\ \hline \\ & 0.21 \pm 0.01 \\ \hline \\ & 0.23 \pm 0.01 \\ \hline \\ & 0.20 \pm 0.01 \\ \hline \\ $	(14-1-2)					
$\begin{array}{ c c c c c c }\hline Mn* Fe NS Mn \times Fe^* & 0.5 & 5 & 30 \\ \hline \\ [Fe] \text{ in solution} & 0.6 & 1.98 \pm 0.17 & 1.69 \pm 0.08 & 1.64 \pm 0.09 & 1.74 \pm 0.07 \\ \hline \\ [Fe] \text{ in solution} & 30 & 1.99 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline \\ [MM] & 300 & 1.85 \pm 0.13 & 1.92 \pm 0.14 & 1.89 \pm 0.10 & 1.89 \pm 0.07 \\ \hline \\ [Mn] \text{ in means} & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline \\ [P] \text{ in unifoliate leaves (%)} & [Mn] \text{ in solution ($\mu$M)} & Fe \text{ means} \\ \hline \\ [Mn] \text{ in solution ($\mu$M)} & [Mn]  in $	[K] in unifoliate le					
$ [Fe] \ in \ solution \\ (\mu M) \  \  \  \  \  \  \  \  \  \  \  \  \ $						1 0 11100115
$ \begin{array}{ c c c c c } \hline [Fe] \ in \ solution \\ (\mu M) & 300 & 1.89 \pm 0.12 & 1.43 \pm 0.06 & 1.99 \pm 0.07 & 1.85 \pm 0.07 \\ \hline Mn \ means & 1.94 \pm 0.08 & 1.68 \pm 0.07 & 1.84 \pm 0.05 & 1.83 \pm 0.04 \\ \hline [P] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn** \ Fe** \ Mn\times Fe* & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 30 & 0.12 \pm 0.01 & 0.22 \pm 0.02 & 0.25 \pm 0.02 & 0.21 \pm 0.02 \\ \hline [Fe] \ in \ solution & 30 & 0.10 \pm 0.01 & 0.14 \pm 0.00 & 0.14 \pm 0.02 & 0.13 \pm 0.01 \\ \hline (\mu M) & 300 & 0.11 \pm 0.00 & 0.16 \pm 0.01 & 0.13 \pm 0.01 & 0.13 \pm 0.01 \\ \hline [S] \ in \ unifoliate \ leaves (\%) & [Mn] \ in \ solution (\mu M) & Fe \ means \\ \hline Mn** \ Fe* \ Mn\times Fe \ NS & 0.5 & 5 & 30 \\ \hline [Fe] \ in \ solution & 0.6 & 0.20 \pm 0.01 & 0.25 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.01 & 0.23 \pm 0.01 \\ \hline [Fe] \ in \ solution & 30 & 0.16 \pm 0.01 & 0.23 \pm 0.00 & 0.22 \pm 0.01 & 0.21 \pm 0.01 \\ \hline (\mu M) & 300 & 0.17 \pm 0.01 & 0.24 \pm 0.01 & 0.20 \pm 0.01 & 0.20 \pm 0.01 \\ \hline \end{array}$				$1.69 \pm 0.08$		$1.74 \pm 0.07$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	[Fe] in solution					
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				- ' '		
		0.6		$0.22 \pm 0.02$		$0.21 \pm 0.02$
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$						
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				- ' '		
[Fe] in solution $(\mu M)$ 30 $0.16 \pm 0.01$ $0.23 \pm 0.00$ $0.22 \pm 0.01$ $0.21 \pm 0.01$ $0.40 \pm 0.01$ $0.17 \pm 0.01$ $0.24 \pm 0.01$ $0.20 \pm 0.01$ $0.20 \pm 0.01$						$0.23 \pm 0.01$
$(\mu M)$ 300 $0.17 \pm 0.01$ $0.24 \pm 0.01$ $0.20 \pm 0.01$ $0.20 \pm 0.01$	[Fe] in solution					
	. ,					

Values are means ± standard error

<sup>\*\*, \*,</sup> NS = significant at P  $\leq$  0.01, significant at P  $\leq$  0.05, and not significant, respectively

**Supplementary Table S2** Main effects and interactions of Mn and Fe in solution on concentrations of nine selected nutrients in soybean trifoliate leaves on a dry mass (DM) basis. A value of 20.3 % DM may be used to convert concentrations to a fresh mass basis. (Experiment 1)

[Mn] in trifoliate leaves (mg kg <sup>-1</sup> )		ГМ	Fe means		
[Mn] in trifoliate leaves (mg kg <sup>-1</sup> )   Mn** Fe** Mn×Fe**		[Mn] in solution (μM) 0.5 5 30			remeans
		$70 \pm 10$	$580 \pm 60$	$3080 \pm 170$	$1700 \pm 300$
[Fe] in solution (μM)	0.6	$70 \pm 10$ $80 \pm 10$	$380 \pm 60$ $230 \pm 10$	$770 \pm 50$	$1700 \pm 300$ $460 \pm 70$
	300	$80 \pm 10$	$230 \pm 10$ $180 \pm 10$	$810 \pm 50$	$470 \pm 80$
		$80 \pm 20$ $80 \pm 10$	$180 \pm 10$ $330 \pm 50$	$810 \pm 30$ $1550 \pm 190$	$880 \pm 130$
[Fe] in trifoliate le	Mn means				
Mn** Fe** Mn×F		0.5	In] in solution (μM) 5	30	Fe means
MIII. Le. MIII.	0.6	$30 \pm 0$	$70 \pm 10$	$50 \pm 10$	50 ± 0
[Eal in colution	30	$30 \pm 0$ $200 \pm 30$	$70 \pm 10$ $110 \pm 10$	$30 \pm 10$ $90 \pm 10$	$30 \pm 0$ $120 \pm 10$
[Fe] in solution (μM)	300	$200 \pm 30$ $230 \pm 70$	$110 \pm 10$ $110 \pm 10$	$90 \pm 10$ $170 \pm 20$	$120 \pm 10$ $170 \pm 20$
(μινι)					$170 \pm 20$ $110 \pm 10$
[Cv] in trifolioto le	Mn means		$150 \pm 30$ $90 \pm 10$ $100 \pm 10$		
[Cu] in trifoliate le Mn** Fe** Mn×F		0.5	<u>In] in solution (μΜ)</u>	30	Fe means
MIII Le MIII.			5		10.1 + 1.0
[Falin colution	0.6	$13.9 \pm 0.9$	$16.1 \pm 1.1$	$23.1 \pm 0.9$	$19.1 \pm 1.0$
[Fe] in solution (μM)	30	$8.4 \pm 0.2$	$6.2 \pm 0.2$	$8.5 \pm 0.4$	$7.9 \pm 0.3$
(μινι)	300	$8.4 \pm 0.6$	$6.4 \pm 0.5$	$9.0 \pm 0.3$	$8.2 \pm 0.3$
[7] ]:   :C  :     1	Mn means	$10.2 \pm 0.7$	$9.6 \pm 1.2$	$13.5 \pm 1.2$	$11.7 \pm 0.7$
[Zn] in trifoliate le			In] in solution (µM)		Fe means
Mn NS Fe** Mn×		0.5	5	30	210 : 20
FF 1 ' 1 '	0.6	$120 \pm 10$	$220 \pm 20$	$240 \pm 30$	$210 \pm 20$
[Fe] in solution	30	60 ± 0	70 ± 0	$70 \pm 0$	70 ± 0
(µM)	300	60 ± 10	60 ± 0	$60 \pm 0$	60 ± 0
FG 31	Mn means	80 ± 10	$110 \pm 20$	$130 \pm 20$	110 ± 10
[Ca] in trifoliate le			In] in solution (μM)		Fe means
Mn NS Fe NS Mn		0.5	5	30	
F 1	0.6	$1.76 \pm 0.08$	$2.09 \pm 0.07$	$1.85 \pm 0.09$	$1.89 \pm 0.06$
[Fe] in solution	30	$1.94 \pm 0.05$	$1.81 \pm 0.05$	$1.74 \pm 0.08$	$1.81 \pm 0.05$
(μM)	300	$2.01 \pm 0.16$	$1.81 \pm 0.06$	$1.72 \pm 0.10$	$1.82 \pm 0.07$
	Mn means	$1.90 \pm 0.06$	$1.91 \pm 0.05$	$1.77 \pm 0.05$	$1.84 \pm 0.03$
[Mg] in trifoliate l		[Mn] in solution (μM)			Fe means
Mn** Fe NS Mn×		0.5	5	30	
F 1	0.6	$0.24 \pm 0.01$	$0.27 \pm 0.00$	$0.32 \pm 0.01$	$0.29 \pm 0.01$
[Fe] in solution	30	$0.32 \pm 0.01$	$0.24 \pm 0.00$	$0.27 \pm 0.01$	$0.27 \pm 0.01$
(μM)	300	$0.34 \pm 0.03$	$0.24 \pm 0.01$	$0.29 \pm 0.01$	$0.29 \pm 0.01$
	Mn means	$0.30 \pm 0.01$	$0.25 \pm 0.01$	$0.29 \pm 0.01$	$0.28 \pm 0.01$
[K] in trifoliate lea			In] in solution (μM)		Fe means
Mn* Fe** Mn×Fe		0.5	5	30	• 10 00=
FD 3 . 1	0.6	$1.89 \pm 0.16$	$2.46 \pm 0.13$	$2.18 \pm 0.08$	$2.18 \pm 0.07$
[Fe] in solution (μM)	30	$1.55 \pm 0.10$	$1.58 \pm 0.06$	$1.77 \pm 0.05$	$1.67 \pm 0.04$
	300	$1.77 \pm 0.06$	$1.63 \pm 0.12$	$1.94 \pm 0.09$	$1.82 \pm 0.06$
	Mn means	$1.74 \pm 0.07$	$1.89 \pm 0.11$	$1.97 \pm 0.05$	$1.89 \pm 0.04$
[P] in trifoliate leaves (%)			In] in solution (µM)		Fe means
Mn** Fe** Mn×F		0.5	5	30	
[Fe] in solution (μM)	0.6	$0.13 \pm 0.01$	$0.33 \pm 0.03$	$0.44 \pm 0.03$	$0.34 \pm 0.03$
	30	$0.11 \pm 0.01$	$0.19 \pm 0.01$	$0.17 \pm 0.01$	$0.16 \pm 0.01$
	300	$0.10 \pm 0.00$	$0.20 \pm 0.02$	$0.18 \pm 0.02$	$0.16 \pm 0.01$
F07 1 12 11	Mn means	$0.11 \pm 0.01$	$0.24 \pm 0.02$	$0.26 \pm 0.02$	$0.22 \pm 0.01$
[S] in trifoliate leaves (%)			In] in solution (µM)		Fe means
Mn** Fe** Mn×Fe**		0.5	5	30	0.5-
	0.6	$0.18 \pm 0.01$	$0.27 \pm 0.01$	$0.27 \pm 0.01$	$0.25 \pm 0.01$
[Fe] in solution	30	$0.19 \pm 0.01$	$0.23 \pm 0.01$	$0.21 \pm 0.01$	$0.21 \pm 0.00$
(µM)	300	$0.19 \pm 0.01$	$0.23 \pm 0.01$	$0.22 \pm 0.01$	$0.22 \pm 0.01$
	Mn means	$0.19 \pm 0.00$	$0.24 \pm 0.01$	$0.23 \pm 0.01$	$0.22 \pm 0.00$

Values are means ± standard error

<sup>\*\*, \*,</sup> NS = significant at P  $\leq$  0.01, significant at P  $\leq$  0.05, and not significant, respectively

**Supplementary Table S3** Main effects and interactions of Mn and Fe in solution on concentrations of nine selected nutrients in sunflower lower alternate leaves on a dry mass (DM) basis. A value of 16.9 % DM may be used to convert concentrations to a fresh mass basis. (Experiment 1)

[Mn] in unifoliate leaf	f tissues (mg kg-1)	[Mn]	(uM)	Fe means
Mn**, Fe**, Mn×Fe*		30	400	i e means
, , , , , , , , , , , , , , , , , , , ,	0.6	$3450 \pm 300$	$8650 \pm 500$	$6050 \pm 610$
[Fe] (μM)	30	$1110 \pm 120$	$5130 \pm 340$	$3120 \pm 460$
r -1 (k)	300	810 ± 70	$4450 \pm 260$	$2630 \pm 400$
	Mn means	$1790 \pm 230$	$6080 \pm 380$	$3950 \pm 340$
[Fe] in unifoliate leaf tissues (mg kg <sup>-1</sup> )		[Mn] (µM)		Fe means
Mn**, Fe**, Mn×Fe		30	400	
	0.6	28 ± 2	26 ± 7	27 ± 4
[Fe] (μM)	30	$158 \pm 28$	58 ± 8	$108 \pm 18$
	300	$127 \pm 22$	$84 \pm 14$	$105 \pm 13$
	Mn means	$104 \pm 15$	56 ± 7	80 ± 9
[Cu] in unifoliate leaf	tissues (mg kg <sup>-1</sup> )	[Mn]	(μM)	Fe means
Mn NS, Fe**, Mn×Fe	**	30 400		
	0.6	$14.8 \pm 0.6$	$25.5 \pm 3.7$	$20.1 \pm 2.1$
[Fe] (μM)	30	$11.6 \pm 1.7$	$8.9 \pm 0.4$	$10.2 \pm 0.9$
	300	$8.9 \pm 0.7$	$8.0 \pm 0.5$	$8.4 \pm 0.4$
	Mn means	$11.8 \pm 0.7$	$14.1 \pm 1.8$	$12.9 \pm 1.0$
[Zn] in unifoliate leaf		[Mn]	(μM)	Fe means
Mn*, Fe**, Mn×Fe N	S	30	400	
	0.6	$113 \pm 6$	$98 \pm 10$	$105 \pm 6$
[Fe] (μM)	30	$71 \pm 6$	53 ± 6	$62 \pm 5$
	300	$39 \pm 3$	$36 \pm 3$	38 ± 2
50.7:1.0:: (0.4	Mn means	$74 \pm 6$ $62 \pm 6$		$68 \pm 4$
[Ca] in leaf tissues (%		[Mn]	Fe means	
Mn**, Fe **, Mn×Fe		30	400	2.22 + 0.12
[F-1 (.)M)	0.6	$2.70 \pm 0.14$	$1.97 \pm 0.17$	$2.33 \pm 0.13$
[Fe] (μM)	30	$1.75 \pm 0.12$	$1.04 \pm 0.08$	$1.40 \pm 0.10$
	300	$1.50 \pm 0.09$	$0.89 \pm 0.07$	$1.20 \pm 0.08$
[Mg] in leaf tissues (%	Mn means	$1.99 \pm 0.11$ [Mn]	$1.30 \pm 0.10$	$\frac{1.64 \pm 0.09}{\text{Fe means}}$
Mn**, Fe**, Mn×Fe		30	(μW) 400	re means
Will , I'C , Will^IC	0.6	$0.23 \pm 0.02$	$0.17 \pm 0.02$	$0.20 \pm 0.02$
[Fe] (μM)	30	$0.23 \pm 0.02$ $0.17 \pm 0.02$	$0.17 \pm 0.02$ $0.07 \pm 0.00$	$0.20 \pm 0.02$ $0.12 \pm 0.01$
	300	$0.17 \pm 0.02$ $0.15 \pm 0.01$	$0.07 \pm 0.00$ $0.06 \pm 0.01$	$0.12 \pm 0.01$ $0.11 \pm 0.01$
	Mn means	$0.19 \pm 0.01$ $0.19 \pm 0.01$	$0.00 \pm 0.01$ $0.10 \pm 0.01$	$0.14 \pm 0.01$ $0.14 \pm 0.01$
[K] in leaf tissues (%)		[Mn]	Fe means	
Mn NS, Fe**, Mn×Fe		30 400		1 c means
,	0.06	$4.21 \pm 0.46$	$4.78 \pm 0.56$	$4.49 \pm 0.36$
[Fe] (μM)	30	$2.65 \pm 0.19$	$2.08 \pm 0.16$	$2.36 \pm 0.14$
[2 0] ([22.2)	300	$2.41 \pm 0.25$	$2.30 \pm 0.16$	$2.36 \pm 0.15$
	Mn means	$3.09 \pm 0.23$	$3.05 \pm 0.29$	$3.07 \pm 0.18$
[P] in leaf tissues (%)			[Mn] (µM)	
M**, Fe**, Mn×Fe**		30	400	
[Fe] (μM)	0.6	$0.15 \pm 0.02$	$0.89 \pm 0.23$	$0.52 \pm 0.14$
	30	$0.14 \pm 0.02$	$0.11 \pm 0.01$	$0.12 \pm 0.01$
	300	$0.11 \pm 0.01$	$0.11 \pm 0.01$	$0.11 \pm 0.01$
	Mn means	$0.13 \pm 0.01$	$0.37 \pm 0.10$	$0.25 \pm 0.05$
[S] in leaf tissues (%)	L	[Mn]	(μM)	Fe means
Mn NS, Fe**, Mn×Fe		30	400	
FT 7 ( 3.5)	0.6	$0.51 \pm 0.03$	$0.52 \pm 0.07$	$0.51 \pm 0.03$
[Fe] (μM )	30	$0.38 \pm 0.04$	$0.29 \pm 0.03$	$0.33 \pm 0.03$
	300	$0.32 \pm 0.03$	$0.29 \pm 0.03$	$0.30 \pm 0.02$
Values are means + star	Mn means	$0.40 \pm 0.02$	$0.36 \pm 0.03$	$0.38 \pm 0.02$

Values are means  $\pm$  standard error

<sup>\*\*, \*,</sup> NS = significant at  $P \le 0.01$ , significant at  $P \le 0.05$ , and not significant, respectively

**Supplementary Table S4** Effects of Mn and Fe in solution on the concentrations of micronutrients and macronutrients in soybean and sunflower leaf tissues on a dry mass basis (Experiment 3).

Tissue	Solution composition (µM)		Micronutrient concentration in leaf tissues (mg kg <sup>-1</sup> )						
	[Mn] [Fe] [Mn]		[Fe]	[Fe] [0		Cu]	[Zn]		
Soybean unifoliate leaf	5	0.6	380 ±	50	67 ± 6		$20.3 \pm 2.5$	$170 \pm 11$	
	5	30	160 ±	10 14	$46 \pm 13$		$7.8 \pm 0.6$	78 ± 5	
Soybean trifoliate leaf	5	0.6	360 ±	30	39 ± 2		$13.2 \pm 1.2$	66 ± 4	
	5	30	190 ±	20 1	$10 \pm 10$		$7.2 \pm 0.2$	45 ± 3	
Sunflower alternate leaf	30	0.6	$3100 \pm 2$	260	24 ± 2		$15.0 \pm 0.2$	79 ± 5	
	30	30	1020 ±	160	62 ± 6		$9.4 \pm 0.6$	39 ± 2	
Tissue	Solution composition (µM)		Macronutrient concentration in leaf tissues (%)						
	[Mn]	[Fe]	[Ca]	[Mg]	[]	K]	[P]	[S]	
Soybean unifoliate leaf	5	0.6	$2.24 \pm 0.12$	$0.28 \pm 0.03$	2.0	$7 \pm 0.04$	$0.12 \pm 0.01$	$0.19 \pm 0.01$	
	5	30	$2.12 \pm 0.07$	$0.17 \pm 0.01$	1.9	$7 \pm 0.11$	$0.09 \pm 0.01$	$0.16 \pm 0.01$	
Soybean trifoliate leaf	5	0.6	$1.29 \pm 0.09$	$0.23 \pm 0.03$	1.7	$8 \pm 0.07$	$0.18 \pm 0.02$	$0.22 \pm 0.02$	
	5	30	$1.14 \pm 0.07$	$0.19 \pm 0.01$	1.5	$4 \pm 0.14$	$0.15 \pm 0.02$	$0.21 \pm 0.01$	
Sunflower alternate leaf	30	0.6	$3.03 \pm 0.27$	$0.29 \pm 0.02$	3.0	$6 \pm 0.04$	$0.15 \pm 0.01$	$0.62 \pm 0.05$	
	30	30	$1.96 \pm 0.63$	$0.22 \pm 0.01$	1.7	$1 \pm 0.13$	$0.09 \pm 0.01$	$0.28 \pm 0.02$	

Values are means ± standard error