Report on NLWRA Theme 5, Project 4c: Acidic soils and acidification, Assessment of effects of acidity on plant yield.

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Plant growth responses to soil acidity are usually caused by toxic effects of the amount of Al and Mn in the soil solution rather than by the concentration of H^+ ions in solution. Therefore correlations between soil pH and plant growth are only indirect indicators of the causes of decline in plant growth. Furthermore the relationship between soil pH and the amount of Al in the soil solution is usually well defined and stable through time for a given soil but varies quite widely between soils. Similar relationships between soil pH and the amount of Mn in the soil solution are less well defined for a given soil, mainly because the redox potential as well as the pH affect the solubility of Mn minerals and oxides. Under similar redox conditions however the amount of Mn in solution increases as the pH declines and decreases with increasing pH in a predictable fashion. As for Al, the solution Mn – pH relationships also vary considerably between soils developed from different parent materials and through different weathering histories.

Models used to estimate the effects of soil acidity on plant yields therefore need to account for differences between soils in the relationship between solution concentrations of Al and Mn and the soil pH. This report outlines a scheme for allocating soils to seven classes with significantly different relationships between the soil pH and the concentration of Al and Mn in solution. Research on the response of different cultivars to changes in pH on different soils has also shown that the amount of easily reducible MnO_2 (ER MnO_2) in the soil can enable a plant to tolerate higher concentrations of solution Al at moderately toxic Al concentrations. Therefore the amount of easily reducible MnO_2 has also been estimated for the seven Al/Mn solubility classes.

Soil Al and Mn solubility classes:

The inputs required for the yield equations are the pH of the 10-20 and 20-50 cm layers, Al_{Ca}, Mn_{Ca} and $ERMnO_2$ for the 0-10 cm layer and the sensitivity class of the species being grown. Since Al_{Ca} and Mn_{Ca} soil test data is often not available but pH values are available, then an alternate method of estimating Al_{Ca} and Mn_{Ca} from pH is needed. Soils vary in the solubility of Mn and Al as soil pH changes. The empirical relationship $-\log Al_{Ca} = a_{4s} + b_{4s} *(pH_{Ca})$ is a reasonably stable soil characteristic, so long as the soil sample is taken after most of the lime applied to increase the soil pH has dissolved. Data from the experiments used to establish a_{4s} and b_{4s} for the soils typical of each soil class show the slope increases and the intercept decreases during the first 2 years after lime application. The result is that the line pivots over time around the point without lime. This behaviour is thought to be due to residual lime dissolving during the shaking period used to obtain the extract for pH and Al measurements. The pH increases during the 1 hour shaking period but the solution Al concentration responds more slowly (Conyers, personal communication). The functions in Table 4 are for data obtained 2 years after lime application unless otherwise indicated. The negative logarithm of Al_{Ca} is highly correlated with pAl, representing the negative logarithm of the Al^{3+} ion activity in the soil solution (Conyers et al., 1991). Therefore it is used in the model as a basis for converting soil pH values to equivalent Al concentrations. This transformation and the equivalent function for Mn_{Ca}, means the toxic factors that determine yield in the model are Al and Mn rather than pH.

Seven soil Al-Mn solubility classes have been established as a basis for estimating Al_{Ca} and Mn_{Ca} from pH (Table 4). Each class is represented by a particular soil that has been chosen as a median representative for the class. In fact there is a continuous range of soils in nature, but this set of classes covers the expected range of Al and Mn solubility from extremely low solubility (e.g. low Al solubility in some Alpine peat soils) to high Al solubility in soils containing a significant amount of gibbsite (class 7).

Soils have been divided into 7 solubility classes. The median soil type used to define each class is shown in Table 1.

1. Very low Al solubility; low Mn solubility; very low ER MnO_2 concentration (VLAl; VLMn; VLMnox)
2. Low Al solubility; high Mn solubility; high ER MnO_2 concentration (LAl; HMn; HMnox)
3. Low Al solubility; very high Mn solubility; very high ER MnO_2 concentration (LAl; VHMn; VHMnox)
4. Moderate Al solubility; moderate Mn solubility; moderate ER MnO_2 concentration (MAl; MMn; MMnox)
5. High Al solubility; low Mn solubility; low ER MnO_2 concentration (HAl; LMn; LMnox)
6. High Al solubility; very low Mn solubility; very low ER MnO_2 concentration (HAl; VLMn; VLMnox)
7. Very high Al solubility; high Mn solubility; low ER MnO_2 concentration (VHAl; HMn; LMnox)

Table 1: Al - pH and Mn - pH relationships, easily reducible MnO_2 concentrations and typical soil types in 7 soil Al/Mn solubility classes.

Soil Al/Mn solubility class	Soil type examples (soil representative of class in parenthesis)	$-\log Al_{ca} = a_{3s} + b_{3s}.pH_{ca}$		$^{\#\#}-\log Mn_{ca} = b_{3s} + d_{3s}.pH_{ca}$		*ER MnO_2
		a_{3s}	b_{3s}	b_{3s}	d_{3s}	(µg/g)
1. VLAl; VLMn; VLMnox (organic soils with all reactive Al complexed by organic matter)**	Neutral, alkaline and acid peats, alpine humus soils, humus and peaty podzols (Alpine peat, Tasmania)	-13.8	5.79	2.3	0.41	<25
2. LAl; HMn; Hmnox (weakly weathered soils)	Red, black and red-brown earths, massive and cracking clay soils, prairie and chocolate soils and mildly acid soils developed on highly basic parent materials (basalt, mafic rocks). (Red earth, Wagga Wagga)	-1.246	1.399	1.9	0.41	225 (150 – 300)
3. LAl; VHMn; VHMnox (weakly weathered, recently acidified soils)	Podzolised earths and other recently acidified, weakly weathered soils containing sources of Mn oxides. (Podsolised red earth, Book Book)	-1.181	1.330	1.7	0.41	400 (>300)

4. MAl; MMn; MMnox (moderately weathered soils developed on parent materials high in SiO_2)	Solodics, mildly developed podzolics. (Yellow solodic, Corienbob)	-1.110	1.291	2.1	0.41	175 (100 – 250)
5. HAl; LMn; LMnox (highly weathered soils, high in SiO_2)	Strongly developed podzolics, moderately acid podzols. (Red podsolic, Mannus)	-1.068	1.219	1.94	0.41	75 (< 100)
6. HAl; VLMn; VLMnox (very highly weathered soils, high in SiO_2)	Acid earthy sands, other highly acid sands and podzols. (Acid earthy sand, Binnaway)	-1.037	1.293	2.3	0.41	25 (<50)
7. VHAl; HMn; Lmnox (highly weathered soils, high in Fe and Al oxides)	Kraznozems, zanthozems, and highly acid euchrozems, red, brown and yellow earths, chocolate and prairie soils. (Kraznozem, Robertson)	-1.622	1.279	1.9	0.41	50[#] [25-75] (200 – 300)

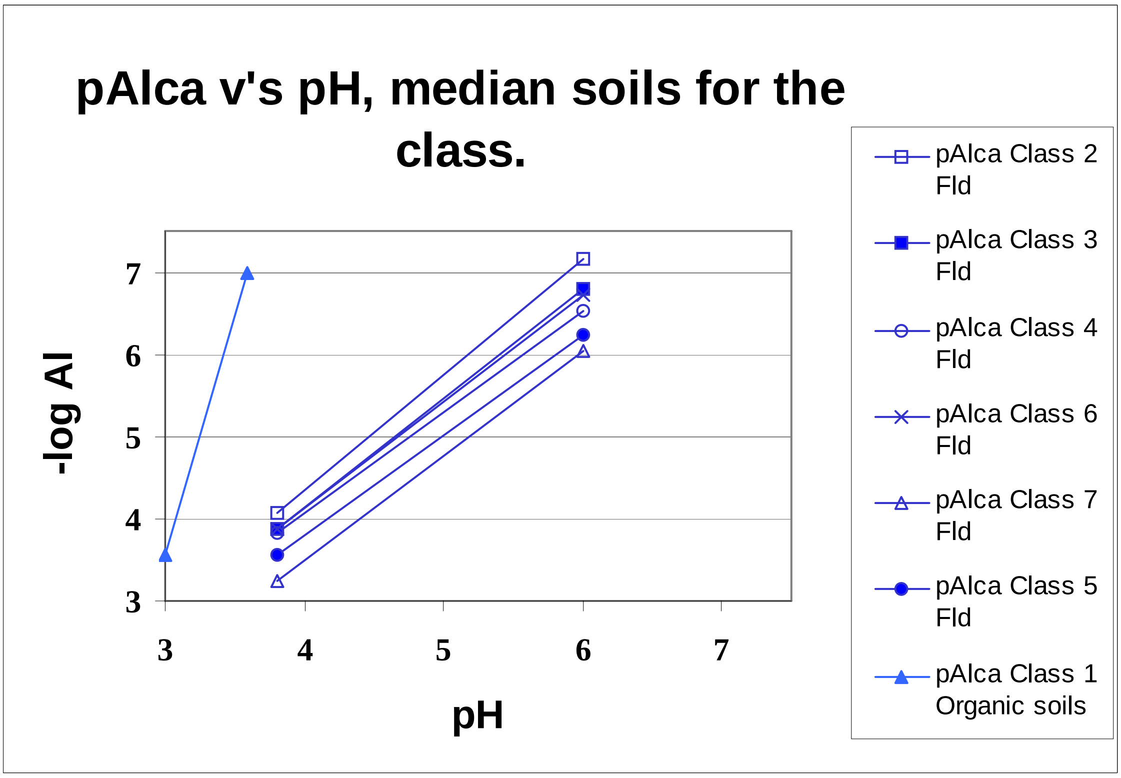
* Easily reducible manganese measured in a 0.2% hydroquinone, 1.0 M ammonium acetate-pH 7.0 extract (As for Bromfield et al.(1983b) but with a 1 hour rather than a 0.5 hour shaking period).

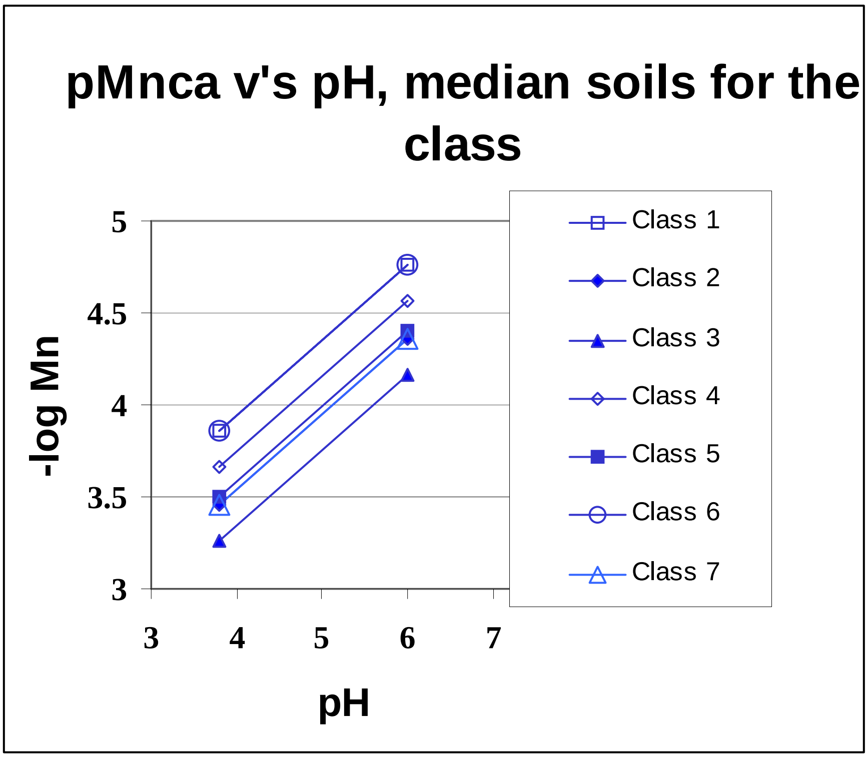
[#] For these soils a proportion of the Mn^{2+} extracted in the hydroquinone extract is probably Mn^{2+} that has desorbed from sites where it has been specifically adsorbed on Fe and Al oxides (ie. not exchangeable Mn^{2+} in the double layer of exchangeable cations). Until better evidence is obtained only a quarter of the Mn extracted from these soils in the easily reducible MnO_2 extract is considered to be MnO_2 (the figure in parenthesis).

** For the organic soil class two alpine peats from Tasmania were used to establish the pH *v's* –log Alca relationship (Conyers, pers. comm.) and the Mn v's pH relationship, in the absence of better data, has been estimated to be comparable with an acid earthy sand.

Plots of the functions relating Al_{Ca} and Mn_{Ca} to pH (Table1) are illustrated in Figure1. For Al Classes 2 and 3 have the same characteristics and for Mn Classes 1 and 6, and 2 and 7 are allocated similar solubility relationships. The peats (Class 1) have been provisionally allocated to the same class as acid earthy-sands in the absence of data to indicate otherwise. This means the Mn status is equivalent to mineral soils that are low in total Mn in both Mn^{2+} and MnO_2 forms. It is assumed that the Mn is in the form of Mn^{2+} but is strongly adsorbed on the organic matter so there is a relatively low Mn^{2+} concentration in solution at all pH values.

Figure 1: Relationships between soil pH and Al and Mn in the 1:5 soil:$CaCl_2$ extract (-log(moles/L)) for the 7 soil Al/Mn classes.


pAlca v's pH, median soils for the class.



Allocation of soils to the Al/Mn solubility classes:

The solubility of Al and Mn across a range of pH varies between soils because of differences in the soil composition. In turn the soil composition is a reflection of the parent material and the weathering history of the soil. In the following scheme the soil parent material is considered in three categories, highly basic parent materials (eg. basalt, diorite, mafic rocks), parent materials with intermediate SiO_2 content (60 to 90%) and extremely siliceous parent materials (>90% SiO_2) (Gray and Murphy, 1999). Rainfall and soil pH at the top of the B horizon have been used as indicators of the intensity of weathering. Lower soil pH and higher rainfall have been associated with higher Al solubility at a given pH. For Mn the situation is more complex. For soils dominated by SiO_2, increased weathering leads firstly to mobilisation of mineral Mn into easily reducible oxide forms, then to decreased total Mn in the soil. In contrast soils high in Fe oxides retain Mn during soil development because of adsorption on the oxide surface, probably as adsorbed Mn^{II} rather than as easily reducible oxides in the Mn^{IV} oxidation state. In addition soil type has been used where soil types can be exclusively allocated to an Al/Mn solubility class. Examples are: i) soils that are calcareous throughout the profile; ii) soil types such as kraznozems that consistently contain gibbsite, the most soluble form of Al; iii) organic soils where the total Al reserves in the soil can be in the form of organic complexes; and iv) non-calcareous sands with composition dominated by SiO_2 and that are very low in total Al.

The following classification system is proposed as a basis for allocating soils to the 7 Al/Mn solubility classes:

Soil group A (all soils):

- **Group A soils exclusive to Al/Mn class 1**:

Organic soils: PPF (principal profile form, Northcote) = O (GSG (Great Soil Group) = neutral, alkaline and acid peats and alpine humus soils)

High OM, low total Al soils: PPF = Uc2.20, 2.33 to 2.36 (GSG = humus podzols); Uc4.33 (GSG = peaty podzols)

- Group A soils conditional to Al/Mn class 1: nil
- Group A soils not in Al/Mn class 1: **Go to soil group B**

Soil group B:

- **Group B soils exclusive to Al/Mn class 2**:

  Soils calcareous through the profile: PPF = Gc soils (GSG = grey, brown and red calcareous soils); Uc1.1, 1.3, Um1.3, 5.1, 6.2 (GSG = calcareous sands.
- Group B soils conditional to Al/Mn class 2:

  PPF = Um5.6 and Um6.4:
    - pH A horizon > 7.0:; **Al/Mn class = 2 (GSG = medium textured grey, brown and red calcareous soils)**
    - pH A horizon < 7.0:
      - pH upper B horizon > 5.5: **Al/Mn class = 2 (GSG = medium textured grey, brown and red calcareous soils)**
      - pH upper B horizon <= 5.5: **Go to soil group C**

  Highly basic, non-calcareous parent material (eg. basalt, gabbro, serpentine, etc.):
    - Rainfall < 1000 mm/annum
      - pH of upper B horizon > 5.0: **Al/Mn class = 2 (chernozem, prairie, some chocolate soils, black earths, some grey, brown and red clays)**
      - pH of upper B horizon < 5.0: **Al/Mn class = 3 (moderately acidified forms of chernozem, prairie, some chocolate soils, black earths, some grey, brown and red clays)**
    - Rainfall >1000 mm/annum
      - pH of upper B horizon > 4.5: **Al/Mn class = 3 (moderately acidified forms of chernozem, prairie, some chocolate soils, black earths, some grey, brown and red clays)**
      - pH of upper B horizon <= 4.5: **Al/Mn class = 7 (highly acidified forms of chernozem, prairie, some chocolate soils, black earths, some grey, brown and red clays that contain significant quantities of gibbsite or amorphous $Al(OH)_3$)**

  Other parent materials, mostly soils developed on parent materials with intermediate SiO_2 content (usually 60 to 90 %):
    - Rainfall < 600 mm/annum
      - pH of upper B horizon > 5.5: **Al/Mn class = 2 (a large range of weakly weathered soils that have been slightly acidified including red, black, red-brown and yellow earths, calcareous red earths, massive and cracking grey, red and brown clays, non-calcic brown soils, alluvial soils, solonchaks, rendzina and terra rossa soils, solonised brown soils, desert loams and hardpan soils,)**
      - pH of upper B horizon <= 5.5: **Go to soil group C**
    - Rainfall >= 600 mm/annum: **Go to soil group C**
- Group B soils not in Al/Mn class 2:

Sands other than calcareous sands: PPF = Uc5.2 **(GSG = earthy sands)**; Uc1.2, Uc5.1 **(siliceous sands)**; Uc2.1, Uc3, Uc4.1, Uc4.3 **(leached sands)**; Uc6.14 **(structured sands)**
Go to soil group D

Soil group C:

- Group C soils exclusive to Al/Mn class 3: nil
- Group C soils conditional to Al/Mn class 3:
  Parent materials of intermediate SiO_2 content (60 to 90 %):
    - Rainfall <800 mm/annum
        - pH upper B horizon > 5.0: **Al/Mn class = 3 (a large range of weakly weathered soils that have been moderately acidified, including red, black, red-brown and yellow earths, calcareous red earths, massive and cracking grey, red and brown clays, non-calcic brown soils, alluvial soils, solonchaks, rendzina and terra rossa soils, solonised brown soils, desert loams and hardpan soils,)**
        - pH upper B horizon <= 5.0: **Go to soil group D**
    - Rainfall >= 800 mm/annum: **Go to soil group D**
- Group C soils not in Al/Mn class 3: nil

Soil group D:

- Group D soils exclusive to Al/Mn class 4: nil
- Group D soils conditional to Al/Mn class 4:
  Non-calcareous sands from soil group A (Very highly siliceous parent materials):
    - All rainfall classes
        - pH upper B horizon > 5.0: **Al/Mn class = 4 (weakly acidified sands)**
        - pH upper B horizon <= 5.0: **Go to soil group E**

  Soils with parent materials of intermediate SiO_2 content (60 to 90 %) from soil group C:
    - Rainfall <1000 mm/annum
        - pH upper B horizon > 5.0: **Al/Mn class = 4 (typical solodics and mildly developed and acidified podzolics)**
        - pH upper B horizon <= 5.0: **Go to soil group E**
    - Rainfall >= 1000 mm/annum: **Go to soil group E**

- Group D soils not in Al/Mn class 4: nil

Soil group E:

- Group E soils exclusive to Al/Mn class 4: nil
- Group E soils conditional to Al/Mn class 4:
  Non-calcareous sands from soil group D (Very highly siliceous parent materials):
    - All rainfall classes
        - pH upper B horizon > 4.5: **Al/Mn class = 5 (moderately acidified sands)**
        - pH upper B horizon <= 4.5: **Al/Mn class = 6 (strongly acidified sands)**

Soils with parent materials of intermediate SiO_2 content (60 to 90 %) from soil group D:

- % clay in A horizon > 20 (separates duplex soils from earths and higher texture)
  - Rainfall <1500 mm/annum
    - pH upper B horizon > 4.5: **Al/Mn class = 5 (moderately acidified earths to clays)**
    - pH upper B horizon <= 4.5: **Al/Mn class = 7 (highly acidified earths to clays)**
  - Rainfall >1500 mm/annum:
    - pH upper B horizon > 4.5: **Al/Mn class = 5 (moderately acidified earths to clays)**
    - pH upper B horizon <= 4.5: **Al/Mn class = 7 (highly acidified earths to clays)**
- clay in A horizon <= 20
  - All rainfall (> 800 mm/annum by default)
    - pH upper B horizon > 4.5: **Al/Mn class = 5 (strongly developed and podzolics, and podzols)**
    - pH upper B horizon <= 4.5: **Al/Mn class = 6 (very strongly developed and acidified podzolics and highly acid podzols)**

- Group E soils not in Al/Mn class 4: nil

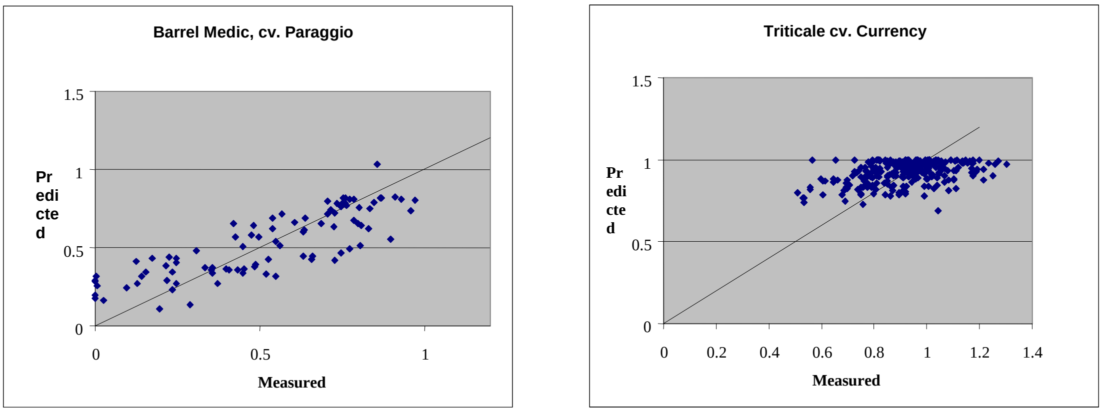
A plant yield model relating plant response to changes of pH on different soils:

The yield model has been fitted to data from 4 field experiments. In these experiments the response of Currency triticale, Matong wheat and Schooner barley to lime was measured over three years at 4 sites in the Wagga Wagga area (Helyar et al., unpub) (and at 4 sites in the Rutherglen area (Slattery and Coventry, 1993).) In addition the response of Paragio barrel medic, Junee subterranean clover and Tauro yellow serradella to lime was measured at the 4 Wagga Wagga sites over three years (Helyar et al., 1992). The response curves for Paragio barrel medic were included when fitting the data to complete the set of species from those very highly susceptible to damage in acid soils (barrel medic), to moderately susceptible cereals (Schooner barley), slightly tolerant cereals (Matong wheat) and highly tolerant cereals (Currency triticale). The soil pH (0-10 cm) in each trial was increased using 4 lime rates and decreased using 1 or 2 rates of elemental sulphur to give a pH range between 3.8 to 4.0 on the most acid treatment and 5.5 to 6.0 at the highest rate of lime.

The soil data against which the model was fitted was the pH of the 10-20 and 20 to 50 cm layers, and the Al_{Ca} and Mn_{Ca} concentrations in solution (mg/L) in the 1:5, soil:0.01 M $CaCl_2$ extract used to measure the pH of the 0-10 cm layer. These measurements were made on soil samples bulked from 10 cores per plot taken from individual plots in the experiments before planting in the second and third years. In year 1 the soil samples were collected in November after the lime and S had had time to react.

Examples of the predicted compared with the actual yields for the most tolerant (Currency triticale) and least tolerant (Paragio barrel medic) species are shown in Figures 1a) and 1b). The data points are for individual plots and include results from 3 seasons and all lime and acid rates for the four sites.

Figure 1: Predicted v's measured relative yields for the most tolerant and least tolerant species used in the curve fitting process.



A number of equations were used in the fitting process. It is known that effects of acid soils on plant growth include effects of Al and Mn toxicities, and in some cases H^+ toxicity, and that these toxicities can be caused by low pH in any or all sections of the root zone. In addition different plant species and varieties have different degrees of tolerance to each of the toxic ions. Still further complications arise because of effects of the soil easily reducible MnO_2 concentration in providing plants with a degree of protection from Al toxicity (Ring et al., 1993). Therefore many variables affect the way a given plant responds to changes in the pH and soluble Al and Mn in various sections of the root zone. This means it is unlikely that the normal ranges of all these variables will be fully represented in any data set that can be used to fit to an explanatory yield model.

Therefore the form of equation that was accepted had to include all the variables that have been shown to affect the response of plants to soil acidity in some environments. Where a variable was poorly represented in the data set it would have a commensurately small effect on determining the 'best fit' equation. Qualitative assessments were then used to accept equations that were not the best fit equations for the data set, but that included all the important factors operating in the known direction for each factor.

Equation (26) describes the relative response of plants (0 to 1 scale) to changes in Mn_{Ca} ($\mu g\ ml^{-1}$), Al_{Ca} ($\mu g\ ml^{-1}$), and easily reducible MnO_2 ($ERMnO_2$ in μg Mn g soil^{-1}) in the surface 10 cm layer of soil:

$$Y_a\left[Al(pH_1), Mn(pH_1), EM\right] = \frac{1}{1 + \dfrac{a_Y Mn_{Ca} + b_Y Al_{Ca}}{1 + c_Y Mn_{Ca} + d_Y Al_{Ca}} + \dfrac{e_Y ERMnO_2}{f_Y + ERMnO_2}} \qquad (26)$$

where Al and Mn are function of soil pH, characterised by soil types. Equation 27) describes the effect of the pH of the 10-20 cm (pH_2), and 20-50 cm (pH_3) layers on the relative yield:

$$Y_b(pH_2, pH_3) = \frac{1}{1 + \frac{g_Y}{h_Y + pH_2 + pH_3}} \qquad (27)$$

where a_Y, b_Y, c_Y, d_Y, e_Y, f_Y, g_Y and f_Y are coefficients. The coefficients for plants in different tolerance classes are shown in Table3).

The relative yield is calculated by

$$Y = \frac{Y_a\left[Al(pH_1), Mn(pH_1), EMn\right]Y_b(pH_2, pH_3)}{Y_a\left[Al(6.5), Mn(6.5), EMn\right]Y_b(6.5, 6.5)} 100\% \qquad (28)$$

Equation (28) estimates relative yield related to pH=6.5, which is assumed no acid effect.

The terms pH_1, pH_2 and $ERMnO_2$ are required to take account of effects on plant growth of the depth of acidity, and of the effect of the easily reducible MnO_2 concentration in the soil on protecting roots from soluble Al. Evidence for the protective effect of MnO_2 has been demonstrated in glasshouse experiments (Conyers et al., 1991; Ring et al., 1993). Observations of minimal responses of sensitive plants to lime on high MnO_2 soils in the field at pH values below 4.5, indicate this effect is also important in field conditions (Fenton, Conyers, Helyar, Pers. comm.).

There is no effect of pH below 50 cm because the data set did not include severely acid soils at that depth. Therefore the model assumes effects of acidity below this depth are not large. This assumption is likely to be in error for soils that have high pH in the surface 50 cm with low pH below this depth. The most likely situation where this could occur is where the surface layers of an acid soil that was severely acid in the whole root zone, have been ameliorated using lime. If the soil is severely acid in the top 50 cm, where most of the root length occurs, further declines in yield due to acidity deeper in the profile are likely to be small.

The effects of Mn and Al on plant growth occur together in this model. There is no explicit recognition that tolerance to Al and Mn are independently inherited. The equation coefficients for the different tolerance categories therefore reflect the mix of Al and Mn tolerance that was present in the cultivars involved in the data set. This problem may need to be addressed in future if experience shows that the model performs poorly with other plants. It is possibile however, that plant tolerance to Al and Mn is usually selected for in parallel because most soils present plants with both increased Al and Mn as the pH declines. Thus the model may be useful for a wide range of plants despite the fact that some species and cultivars have long been known to be tolerant to Al and susceptible to Mn and vice versa (Hewett, 1947).

The yield is scaled for each enterprise and year of the rotation by providing an input for the expected yield (averaged across a range of seasons) without lime on the paddock. The main guideline for this is the yield that has been historically achieved on the paddock with the current management. A second input, the potential yield given limitations by the climate and good soil profile (best, seasonally averaged district yields under good management), is provided as a check on the limitations imposed by management and to highlight poor inputs. Finally where special ‘rotation effects’ need to be taken into account (e.g. reduced disease due to a break in the disease cycle through use of a ‘disease break-crop’ in the rotation or a decline in soil N status with a particular sequence of non-legume crops), the yield can be multiplied by and index (e.g. 0 to 2.0) to adjust for the rotation effect.

Table 3: Coefficient values for the yield equation** for plants in different tolerance classes.

Tolerance class	Coefficient							
	a_3	b_3	c_3	d_3	e_3	f_3	g_3	h_3
1. VHT*	Yield = average of HT and 100							
2. HT	$2.141 *10^{-4}$	$1.543*10^{-1}$	$13.41*10^{-3}$	$5.064*10^{-3}$	0	0	0	0
3. MT	Yield = average of HT and ST							
4. ST	$48.57 *10^{-4}$	$3.668*10^{-1}$	$98.59*10^{-3}$	$-580.6*10^{-3}$	$0.9181*10^{-2}$	-143.5	$1.895 *10^{-2}$	-8.308
5. SS	Yield = average of ST and MS							
6. MS	$-29.67*10^{-4}$	$4.107*10^{-1}$	$-14.70*10^{-3}$	$-147.3*10^{-3}$	$-42.119*10^{-2}$	22.48	$240.0 *10^{-2}$	-6.336
7. HS	Yield = average of MS and VHS							
8. VHS	$-323.3*10^{-4}$	$17.19*10^{-1}$	$5.796*10^{-3}$	$-489.6*10^{-3}$	$-7545.1*10^{-2}$	155632	$110.6 *10^{-2}$	-7.156

* The codes for the tolerance classes are VHT (very highly tolerant), HT (highly tolerant), MT (moderately tolerant), ST (slightly tolerant), SS (slightly sensitive), MS (moderately sensitive), HS (highly sensitive) and VHS (very highly sensitive).

** Note that for each curve there is a maximum pH (pH_{max}) of 6.5 above which the relative yields do not increase. pH_{max} has been defined to limit the range of response to that observed in the calibration data and to stop extrapolation of the response curves to unrealistic yield values.

Other species and varieties have been tentatively classified in the intermediate classes. The intermediate classes have yields that are the average if the adjacent classes. In the case of VHT plants the yield is the mean of 1.0, the potential yield without limitations due to acidity, and the yield for the HT class (Table 3). Further examples of cultivars that are in the different tolerance categories based on pot experiment data (Helyar and Conyers, 1994) are listed below. Local experience with growth on acid soils and of responses to lime by these species and cultivars in comparison with other plants can be used to estimate tolerance classes for unclassified cultivars. The Al concentration in a uniformly acid root zone (i.e. the data is from pot experiments with well-mixed soil) when the yield is 50% of the yield at a non-limiting pH of pH 6.0 is also shown for each tolerance class.

- VHT(Al_{50} = > 30 mg Al/L): Blackbutt, Echidna, Carbeen, Coolabah and Mortlock oats, Consul Lovegrass, Porto cocksfoot, Italian and Perennial ryegrasses, Danthonia richardsonii, Paros, Madeira and Avila yellow serradella, Siratro, rosedale subterranean clover, 39E and Empat triticale and Microlaena stipoides;
- HT(Al_{50} = 10-30 mg Al/L): Ryesun cereal rye, Denmark, Meteora and Larissa subterranean clover, Cooba oats, Grasslands Maku Lotus pedunculatus, Currie cocksfoot;
- MT(Al_{50} = 5-10 mg Al/L): Dollarbird and Diamondbird wheat, Australian and Holdfast phalaris, Pioneer Rhodes grass, Junee, Goulburn, Seton Park, Clair, Nungarin, Tricala, DalkeithKaradale and Woogenellup subterranean clover;
- ST(Al_{50} = 2.5-5 mg Al/L): Dixie crimson clover, Haifa and Tamar white clover, Stout oats, Zodiac Medicago murex, Suneca, Janz and Hartog wheat, Sirolan, Uneta and Sirosa phalaris, Grasslands Matua prarie grass;
- SS(Al_{50} = 1.5-2.5 mg Al/L): Hula and Irrigation white clover, Danthonia linkii, Biloela and Gayndah buffel grass;
- MS(Al_{50} = 1.0-1.5 mg Al/L): Molopo buffel grass, Hunterfield, Aquarius and Siriver lucerne, Redquin red clover, Eigara yellow serradella, Vulcan and Kiata wheat;
- HS(Al_{50} = 0.5 – 1.0 mg Al/L): Paradona balansa clover Hunterfield and Hunter River lucerne;

- VHS (Al_{50} = 0.2-0.5 mg Al/L): Agropyron spp., Tyrrell tall wheatgrass, WL516 and Nova lucerne, Palestine strawberry clover, Harbinger strand medic, Bigbee and Carmel berseem clover and Kyambro Persian clover.

It is suggested that a good way to test the general applicability of the combined operation of the yield and Al/Mn class models will be to run it for audit surfaces and plants with known responses to lime to see if the results are reasonable for test areas. The Al/Mn class model should also be looked at to test the validity of the pH at the top of the B horizon and rainfall values that have been used in the classification. We are to do this on a large data set (some 5000 soil samples) south and east of Wagga Wagga for which the rainfall varies from 400 to 1200 mm and there is a wide range of pH at the top of the B horizon and of parent materials. This study has not been completed at this time (February, 2001).

Using the yield model in association with the soil and plant tolerance classes:

The plant yield model defined above is used to estimate the relative yield of plants allocated to several Al and Mn tolerance classes. The relative yield of a plant in a given tolerance class is calculated as a function of the pH of three soil layers (0-10 cm, 10-20 cm and 20-50 cm), the Al/pH relationship for the soil, the Mn/pH relationship for the soil and the $ERMnO_2$ concentration in the 0-10 cm layer. The pH values and the Al/Mn class for the soil are the inputs required. If the absolute yield is required the relative yield can be scaled by supplying a value for the potential yield without acidity limitations in the soil profile. This yield is equated to a relative yield of 1.0.

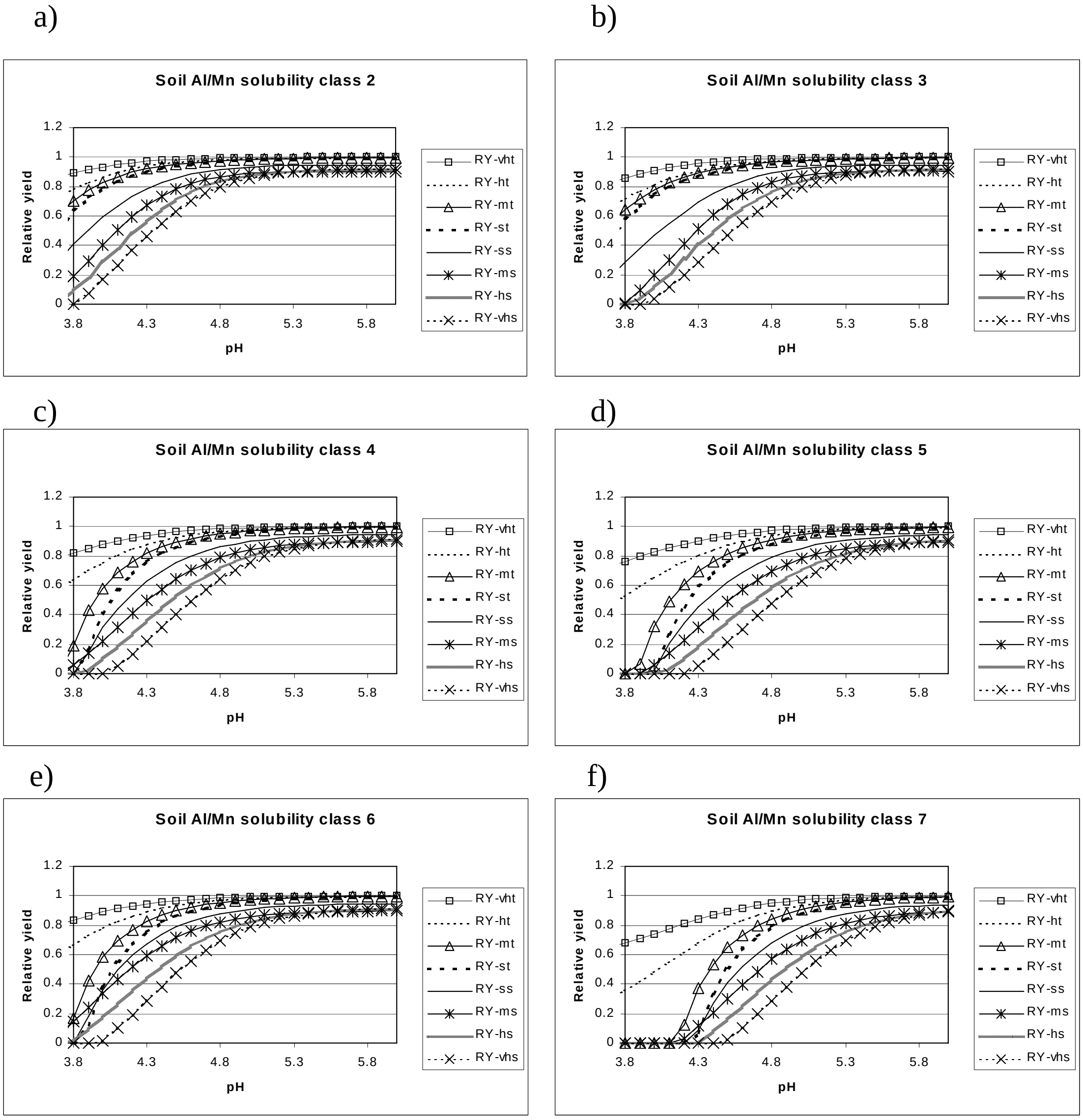
The response of a plant to changes in soil pH are affected by both the Al/Mn solubility class for the soil and the plant tolerance class. These effects are illustrated in Figures 2a) to 2f).

In the NLWRA audit the criteria required by the Al/Mn class classification system described above that are to be available from various ‘Audit surfaces’ are:

- the PPF soil classification;
- the soil parent material in three categories (mafic and ultramafic rocks; typically with % SiO_2 <50; rocks with moderate to high concentrations of SiO_2, typically 60 to 90%; and highly siliceous parent material, typically > 90% SiO_2);
- the average annual rainfall in mm;
- the pH_{Ca} of the top of the B horizon;
- and occasionally the pH_{Ca} of the A horizon.

The table below contains suggestions for the tolerance classes for each plant in the crop and pasture categories used in the audit. For most species there is a range of tolerance among the varieties under cultivation. The tolerance category chosen for a given species is the more tolerant of the varieties that are available. This choice is based on the fact that if farmers know they have an acid soil they will use the most tolerant variety available, because tolerance to soil acidity is seldom coupled with a yield penalty relative to other varieties. For the same reason, the choice of the more tolerant variety is not likely to result in lower yields on more alkaline soils. Hence on these soils the choice of tolerance class will not affect the yield estimate. Where no data on the tolerance of a species was found, a moderately sensitive class (6) has been allocated so responses will not be underestimated. Similarly a moderately tolerant class (3) has been allocated where the plant is known to grow satisfactorily on acid soils but no data on lime responses was found. Readers can assess the validity of the tolerance classes by comparing their experience of yield responses to acidity against the response curves shown for the relevant soil type in Figure 2.

Figure 2: Yield response to changes in soil pH on 6 soil types with different Al and Mn solubility characteristics (and for $pH_{10-20} = 5.0$ and $pH_{20-50} = 6.0$).



Critical assessment of the tolerance classes is welcome because local experience of the responses of individual species and varieties will in many cases be the only available knowledge where published data is not available.

Table 2: Tolerance classes for the plant types considered in the National Soil and Water Audit.

Abs_lev3	**Count**	**Tolerance class**	
	(approx sq km)	**class for audit**	**possible alternative**
Agroforestry	196	3	
Almonds	58	6	
Apples[1]	154	7	
Apricots	103	6	
Avocados	57	3	
Avocados/Mangoes	19	3	
Bananas	51	3	2 From Phil
Barley	40162	6	
Canola	4743	6	
Cereals excluding rice	127	3	
Cereals for hay/silage	1012	1	2
Cherries	23	6	
Chick peas	1852	7	8
Chick peas/Mung beans	5	7	
Coriander	61	7	
Cotton	3781	3	
Faba beans	2550	5	
Fallow	358		
Fennel	24	6	
Field peas	8061	5	
Grain sorghum	5603	4	
Grapes	1014	6	
Lavender	58	6	
Lentils	657	7	
Lupins	7047	2	
Macadamia	166	2	
Maize	2007	4	
Maize/barley	63	6	
Mandarins	15	6	
Mangoes	73	3	
Mandarins/lemon/lime/oranges	15	6	
Millet	119	4	
Mustard	18	4	
Native pasture[2]	3176305	1	2 to 5
Nectarines	43	6	
Non-cereal crops for hay	138	5	
Non-cereal crops for silage/green feed	134	5	
Nurseries/flowers	150	6	
Oats	3516	1	
Oil poppies	116	7	
Oranges	268	6	
Other cereals for grain	34	3	
Other field beans	355	5	
Other sown pastures	182090	2	3, 4

Abs_lev3	**Count**	**Tolerance class**	
	(approx sq km)	**class for audit**	**possible alternative**
Other stone fruit	12	6	
Other vegetables	614	6	
Peaches	42	6	
Peanuts[3]	506	4	3, 2
Pears	54	6	
Pineapples	166	1	
Plums	86	6	
Potatoes	504	2	3
Pure lucerne	14396	7	8
Pyrethrum	99	6	
Residual	394285	5	
Rice[4]	1548	2	
Soybeans	260	3	4
Sugar cane	4312	1	2
Sunflower	1214	6	
Tobacco	38	6	
Triticale	18613	2	3
Turf	263	2	
Vetches	449	5	
Wheat	104848	3	4 to 6
Wheat/grain sorghum	252	3	4 to 6

[1] Sensitive class reflects susceptibility to Ca deficiency in fruit
[2] Tolerance depends on soils at origin
[3] Lime may be needed for Ca deficiency so more sensitive class allocated
[4] Flooded conditions rather than upland

References:

Gray, J. M. and Murphy, B. W. (1999) Parent materials and soils. A guide to the influence of parent material on soil distribution in eastern Australia. 121pp.,Technical Report No. 45 NSW Department of Land and Water Conservation, Sustainable Land and Coastal Management, Parramatta.

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