

## The Correct pH of a Soil – Looking back to go forward. A discussion

David McKechnie (Original Jan 2006 - Modified 2022)

“What is the correct pH of the soil for my plant?” This is a constant question. From my considerations back in 2006, to now (Aug 2022) I make following observations only to subjects of observations and variance of pH.

Various terms have been used to describe the pH of the soil. These include.

Sweet or sour

Acidic, Neutral or Alkaline (Basic)

High, low, or neutral.

For clarity I prefer the actual definition where pH of the soil *solution* is “the negative logarithm of the hydrogen ion activity” (Wild Ed 1988). Where p means negative logarithm and H is the activity coefficient of the hydrogen ion (where  $\gamma$  is the activity coefficient and the hydrogen ion concentration is measured in moles per litre).

Discussion on soil pH go back in the literature. Pettinger in 1935 published information on the potential of nutrients available to the plant at different mineral soil (solution) pH's. A chart (Chart 1) was soon published (Annon. (1935)) from Pettinger's work showing the optimum pH range of nutrient availability for a range of garden and crop plants.

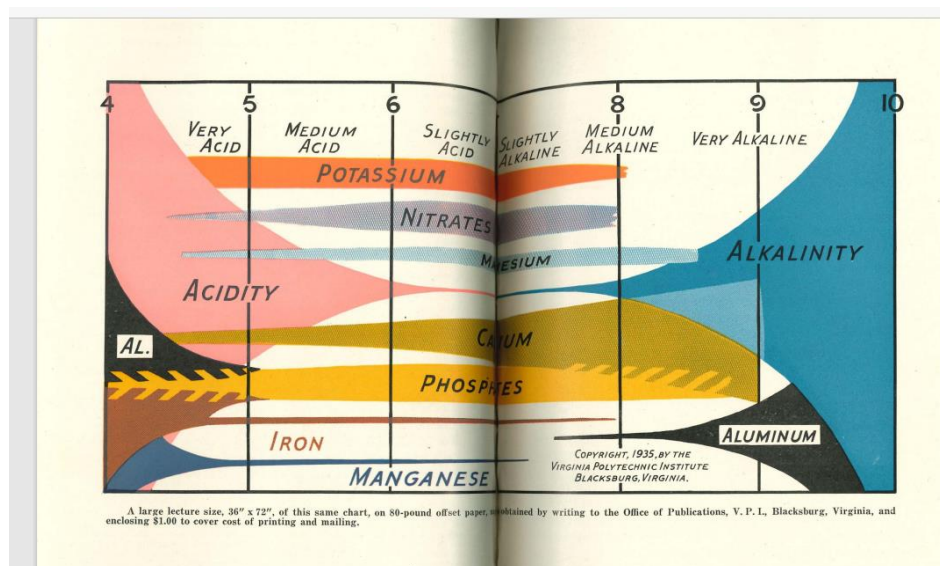


Chart 1: Pettinger 1935.

Pettinger does note two limitations to this chart:

1. “ ....it was hoped that the bands could be drawn so that their respective widths would represent the relative quantities of the various nutrients available to crops in the average soil. It was soon found, however, that this would be impossible.”
2. “ .....that the chart is designed to illustrate only the changes which take place in well-drained mineral soils of the humid regions. No claims are made for its applications to the alkali soils of semiarid regions nor to swampy or highly organic soils, although many of the relations shown may apply wholly or in part to some of these soils also,” .....

And that “The chart really shows, therefore, that the extreme reactions should be avoided, and that the availability of plant foods is most favourable to crops when the soil reaction is between pH 5.5 and 7.0”.

Latter Truog (1947) published the following chart (Chart 2) based on Pettinger (1935) earlier work. Truog made the point that “pH 6.5 is a very favourable reaction as regards the availability of all the elements .....obtained by plants from the soil proper” Importantly this is for a mineral soil. This general comment of “plants require a pH of 6.0 to 6.5” is still used today.

Truog (1947) also made a curve linear representation of the H ion (hydrogen) and OH (hydroxy) concentration in this chart. This is useful when considering if the element or nutrient is in a reduced (acid or low oxygen environment) or oxidised (alkaline or high oxygen environment). So how does this relate to a negative log?

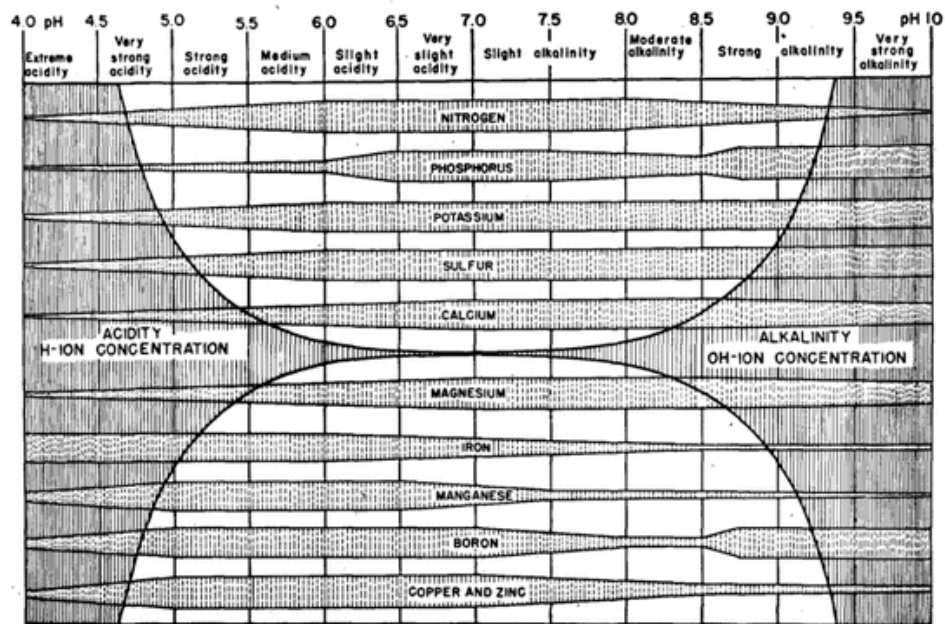


FIG. 1.—Diagram illustrating general trend of relation of soil reaction (pH) and associated factors to the availability of plant nutrient elements. Each element is represented by a band as labeled. The width of the band at any particular pH value indicates the relative favorableness of this pH value and associated factors to the presence of the elements in question in readily available forms (the wider the band the more favorable the influence), *but not to actual amount necessarily present*, this being influenced by other factors, such as cropping and fertilization. The width of the heavily cross-hatched area between the curved lines at any pH is proportional to the hydrogen-ion concentration (intensity of acidity) to the left of pH 7, and to the OH-ion concentration (intensity of alkalinity) to the right of pH 7.

Chart 2: Truog 1947

The negative log was earlier described as an “intensity” of reactions (Pettinger 1935).

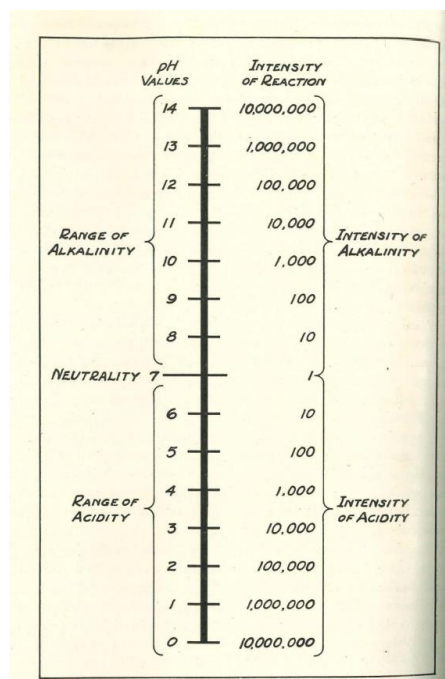
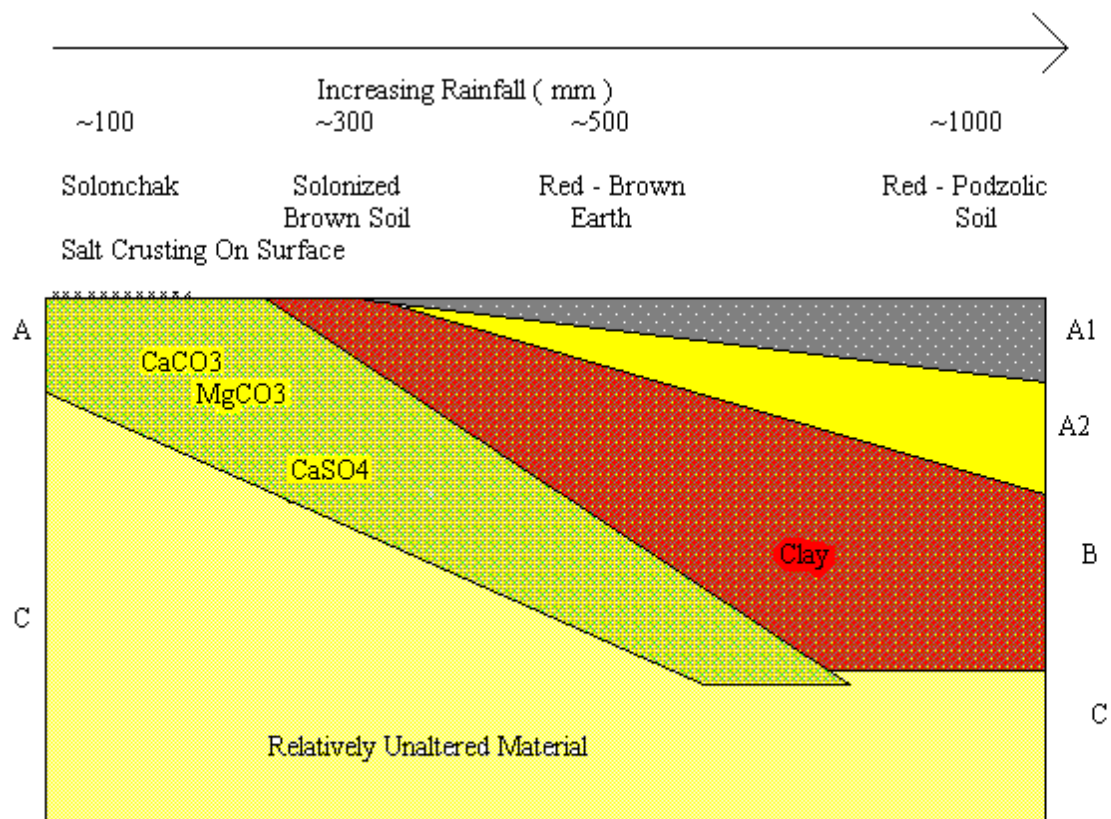


Chart 3: Intensity of reactions. Pettinger 1935

This concept of intensity is useful when consideration is given to soil chemistry. As water has two hydrogen molecules and one oxygen ( $H_2O$ ) pure water is deemed to be neutral (pH 7 -  $HOH$ ). So as the Concentration of hydrogen ion ( $H$ ) decreases (from the acid/neutral to the alkaline) the hydroxyl ion ( $OH$ ) starts to increase. This change from a reduced (an element gains an electron or acid waterlogged conditions) to an oxidised state (an element loses an electron or alkaline aerated conditions) in the soil solution are known as redox (reduction – oxidation) reactions.

These concept of wetting / drying, dry or waterlogged soils is an important consideration to soil pedology (soil formation factors). Where increasing rainfall (irrigation?) leach alkaline salts through the profile - Diagram1.

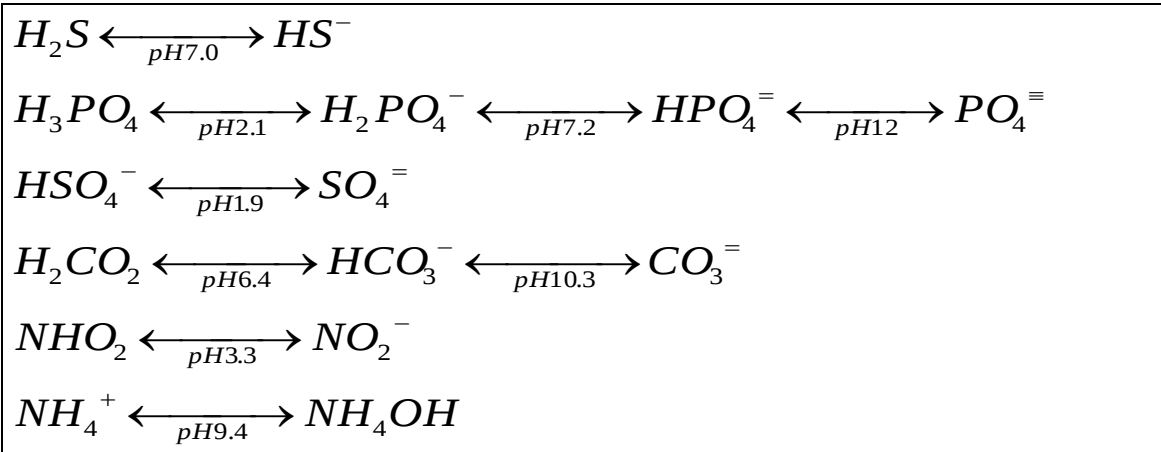


**Diagram 1.** The effect of increasing rainfall on a soil sequence in NSW (From Koppi 1990).

It is the pH/redox reactions that make the soil volume a living or barren organism. Eg “in the pH range 6.5 to 7.5 conditions are most favourable for availability” of phosphorous (Truog 1947) (Also see Lindsay 1979).

Waterlogged soils (reduced) generally have an Eh (redox potential) between +0.2V and -0.4V whilst aerated soil range between +0.3V and +0.8Volts. (Wild Ed 1988 pg 790) (Also see Lindsay 1979).

Eh vs pH can provide graphs giving the stability fields for various compounds in reaction (Baas Becking et al 1960). Some of these naturally occurring non-metallic transformations are presented in table 1.



**Table 1.** Reactions from Stability diagrams (Baas Becking et al 1960)

As can be seen from the above reaction equations, pH performs a distinct role in the dynamics of compound formation, whilst the effects of redox (pe), O(g) and / or CO<sub>2</sub>(g) are not clearly identified. This also affects the availability of nutrients for plant uptake (or nutrient complexing).

Organic matter also can change the optimum availability of nutrients in the soil. Brady (1990) published a similar chart (chart 4) for organic soils as compared to Truog mineral soil but noted the optimum pH to between 5 – 5.5 (See also Handreck and Black 3<sup>rd</sup> ed 2002. pg 91 - 92). Hydroponic solutions (eg quartz sands or inert media) also produce different availability for nutrients (Simply Hydro) Chart 5.

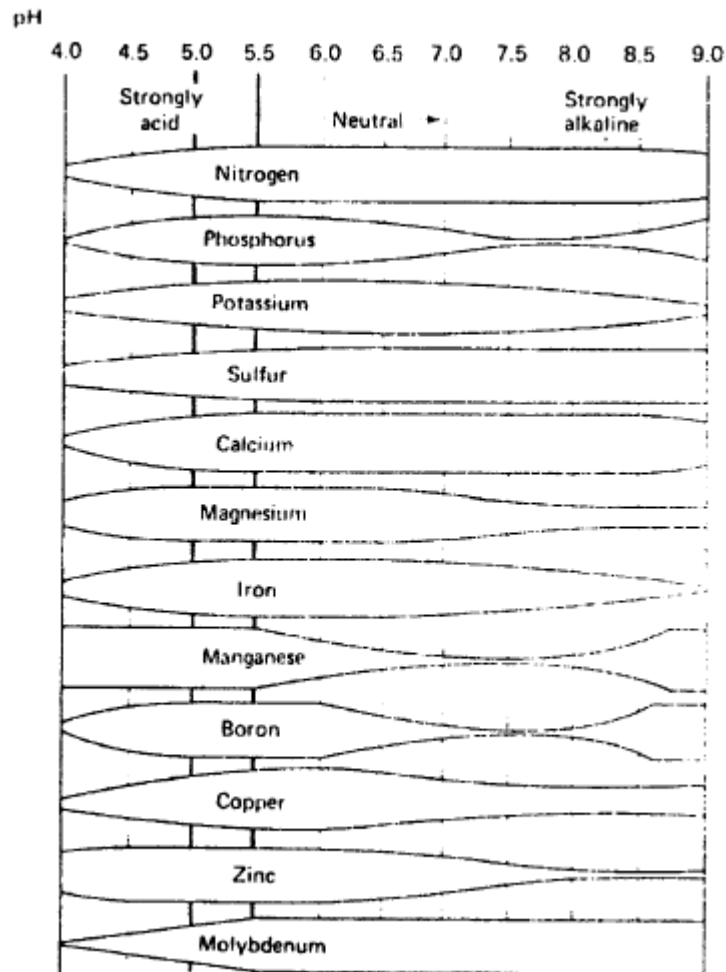


Chart 4 Nutrient availability in an Organic Soil (Brady 1990)

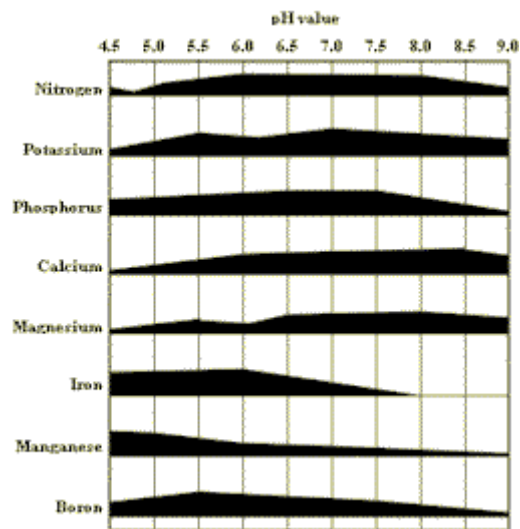


Chart 5 Nutrient availability in a hydroponic solution. Web Site Simply Hydro

Numerous methods are available to measure the pH of the soil. I have divided them into:

- 1) Indication methods eg colour changes
- 2) Direct Method eg measuring an electrical change from a known reference solution (various ratios – various extractants including saturated paste)

Indirect methods include the use of litmus paper or the Saturated Paste colour - Soil pH Test (Inoculo Laboratories). These give a colourimetric change which is then compared to a reference chart. A field method for potential acid sulphate soil uses the change of pH upon the use of hydrogen peroxide using pre and post colorimetric measurements (4E1 Table 3).

Direct methods are those that take an electrical reading from the soil solution. These solutions can range from a saturated paste, 1 part soil to 1part water or to 1 part soil to 10 parts water (Attiwiil and 1990) and direct. (The Australian standard is 1 part soil in 5 parts deionized water or calcium chloride solution).

On an historical notes (Benton Jones 1993) is that up to about 1925 in America litmus paper was used to determine soil pH, hence “The Potassium Thiocyanate Test” was used (the concentrate/soil ratio not given).

It is very important to note the method of pH measurement as the principle is to measure the pH of the soil solution. So, for the same soil the more liquid mixed in will give different pH reading (diluted).

Some of the variation of different pH measure were given by McKechnie (1997), noting that over 21 methods could have been used. These range from saturate extracts (using litmus paper) in early times to 1:1, 1:2, 1:5, 1:10 soil to water or extractant ratios.

| Method Code *                | Variation | Soil      | Type  |
|------------------------------|-----------|-----------|-------|
| Raupach and Tucker           | 0         | Field     | Field |
| pH of 1:5 Soil / Water 4A1   | 0.5-0.6 + | Air Dried | Lab   |
| 1:5 soil 0.01M Ca Cl Dir,4B1 | 0- 0.5-   | Air Dried | Lab   |

**Table 2.** Comparison of Common Australian pH measurements

As can be seen different pH measurements can be half a pH unit out. Whilst some work has been done on laboratory (Mountier et al 1966), field variance (eg Mountier and During 1966), Spatial variance (During and Mountier 1967) and total variance (Mountier and During 1967). For these New Zealand soils total variance was about 0.3 pH units.

| Method Code *                                                                                                                                                                                                                                                                       |     | Variation        | Soil        | Type  | Variation /<br>Used To        | Reference # |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|------------------|-------------|-------|-------------------------------|-------------|
| Raupach and Tucker                                                                                                                                                                                                                                                                  | Nil | Base             | Field       | Field |                               | 1           |
| pH of 1:2 Soil / Water                                                                                                                                                                                                                                                              | Nil | ----             |             | Lab   |                               |             |
| pH of 1:5 Soil / Water                                                                                                                                                                                                                                                              | 4A1 | 0.5-0.6 +        | AD          | Lab   | ( $pH_w$ )                    | 2           |
| 1:5 soil 0.01M Ca Cl Dir,4B1                                                                                                                                                                                                                                                        |     | 0- 0.5-          | AD          | Lab   | Soluble Salts / ( $pH_{Ca}$ ) |             |
|                                                                                                                                                                                                                                                                                     |     |                  |             |       | Variable Surface Charge       | 3           |
| 1:5 soil 0.01M Ca Cl                                                                                                                                                                                                                                                                | 4B2 | 0-0.5-           | AD          | Lab   | Follows 4A1                   | 4           |
| 1:5 soil /1M KCl Dir,                                                                                                                                                                                                                                                               | 4C1 | $\Delta pH^{**}$ | AD          | Lab   | Different Extract             | 4           |
| 1:5 soil /1M KCl                                                                                                                                                                                                                                                                    | 4C2 | $\Delta pH$      | AD          | Lab   | Follows 4A1                   | 4           |
| pH of Na F soln                                                                                                                                                                                                                                                                     | 4D1 |                  | AD          | Lab   | Active Al                     | 4           |
| pH of H <sub>2</sub> O <sub>2</sub>                                                                                                                                                                                                                                                 | 4E1 |                  | Field       | Lab   | Acid Sulphate Soil            | 4           |
| $\Delta pH$                                                                                                                                                                                                                                                                         | 4F1 |                  | Calculation |       | Dominate Electrical Charge    | 4           |
| Notes<br>* Code from Rayment and Higginson 1992<br># 1 / Raupach and Tucker 1959, 2 / Rayment and Higginson 1992 Also See Baker et al 1983, and Ahern et al 1995. 3 / Rayment and Higginson 1992 Also Conyers and Davey 1988, and Ahern et al 1995. 4 / Rayment and Higginson 1992. |     |                  |             |       |                               |             |

**Table 3.** Comparison of Common Australian pH measurements

This is amongst other measurements of pH for different considerations, reasons or uses. (Table 3 ).

Further work in reviewing the available data on methods and variation is needed for local conditions (soils x plants x water x rainfall x time x etc).

Variation in the recorded pH preference of plants has also been given by various authors.

For example:

*Agrostis capillaris (tenius )* Brown Top Bent

| Reference              | pH          | Soil Nutrients         | Soil Moisture |
|------------------------|-------------|------------------------|---------------|
| Beard 1973 (Pg 71)     | 5.5 - 6.5   | fertile (Low Nitrogen) | Moist         |
| Davies and Howard 1994 | 5 - 5.5     | Bsat* 20-45% (Low )    | Not Noted     |
| Grime et al 1988       | 3 - 8 (4-6) | Midly Acidic           | Dryland Moist |

And

*Agrostis stolonifera* var *palustris* Creeping Bent Grass

| Reference            | pH        | Soil Nutrients | Soil Moisture |
|----------------------|-----------|----------------|---------------|
| Beard 1973 ( Pg 71 ) | 5.5 - 6.5 | fertile        | Moist         |
| Grime et al 1988     | 5.5 - >8  | Not Noted      | Wet           |

Reid (1932) found the pH range of creeping and colonial bentgrass to grow well on a fertile soil between pH 4.5 and 8.3. She made twelve notes on the difference of pH and growth with various considerations.

When comparing the plant pH requirements as presented (many other authors have done similar work) and the assumed soil solution pH of 6.5 we can see how creeping bentgrass (*Agrostis stolonifera* var *palustris*) has come to dominate over *Agrostis capillaris* (*tenius*) Brown Top Bent in the turf industry.

| Common Name                | Drought Tolerance | pH Optimum | pH Range  |
|----------------------------|-------------------|------------|-----------|
| Brown Top Bent             | Poor              | 4.0 - 6.0  | 3.0 - 8.0 |
| Creeping Bent              | V. Poor           | 5.0 - 8.0  | 3.0 - 8.0 |
| Tall Fescue                | Good              | 4.7 - 8.5  |           |
| Creeping Red Fescue        | Excellent         | 5.0 - 8.0  | 3.0 - 8.0 |
| Chewings Red Fescue        | Good              | 5.0 - 8.0  | 3.0 - 8.0 |
| Annual Ryegrass            | Medium - Poor     | 6.0 - 7.0  |           |
| Perennial Ryegrass         | Medium to poor    | 5.0 - 8.0  | 4.0 - 8.0 |
| Kentucky Blue grass        | Good              | 5.0 - 8.0  | 3.0 - 8.0 |
| Rough Bluegrass            | Poor              | 6.0 - 7.0  | 4.0 - 8.0 |
| Wintergrass                | Poor              | 5.0 - 8.0  | 4.0 - 8.0 |
| Narrow leaved Carpet grass | Poor              | 4.5 - 5.5  |           |
| Broad leaved Carpet grass  |                   |            |           |
| Common Couch               | Excellent         | 5.5 - 7.5  |           |
| Sth African Couch          |                   |            |           |
| Durban Grass               | Good              | 6          |           |
| Qld Blue Couch             | Poor              | 5.5 - 6.0  |           |
| Centipede Grass            | Medium            | 4.5 - 5.5  |           |
| Bahiagrass                 | Excellent         | 6.5 - 7.5  |           |
| Salt Water Couch           | Excellent         | ?          |           |
| Kikuyu                     | Good              |            |           |
| Buffalo grass              | Medium            | 6.5 - 7.5  |           |

**Table 4.** Various noted pH range for some grasses (various authors or sites)

Plant breeder also need to consider the soil “solution” pH not only of the site where a sample was collected but also the selective growing environment and grow out areas.

pH is also important to know for the appreciation of other chemical reactions and biology in the soil solution environment (Rieke 1969). Eg Worms generally prefer neutral to alkaline soils (Curry 1994 pg30). Changing soil surface pH for dollar spot control (Anon –Jap1997).

I further considered the influence of rainfall variables on soil “solution” pH (and of course soil formation – Pedology). This was “sparked by the works of Turner et al 1996 whom looked at Nutrient inputs from rainfall in New South Wales Forests.

During the review it was evident the “container” type affects readings. Consideration to the variable of influence of the container affecting pH of the sample, either the plastic rain gauge or a “glass” collector was undertaken.

| Date            | Sample   | Low  | High | Mean | Average | Count |
|-----------------|----------|------|------|------|---------|-------|
| 2007            | Gauge    | 4.38 | 6.9  | 5.16 | 5.34    | 20    |
| 2008            | Gauge    | 4.12 | 6.97 | 5.34 | 5.53    | 22    |
| 2009            | Gauge    | 4.3  | 7.96 | 6.03 | 6.06    | 27    |
| 2010            | Gauge    | 4.46 | 6.34 | 5.17 | 5.21    | 40    |
|                 | Averages | 4.32 | 7.04 | 5.43 | 5.54    |       |
|                 |          |      |      |      |         |       |
| 2007            | Glass#   | 4.95 | 6.64 | 5.63 | 5.71    | 29    |
| 2008            | Glass#   | 4.61 | 7.89 | 5.56 | 5.91    | 37    |
| 2008            | Glass    | 4.96 | 6.87 | 5.74 | 4.94    | 8     |
| 2009            | Glass    | 4.84 | 7.11 | 5.85 | 5.85    | 31    |
| 2010            | Glass    | 4.73 | 6.51 | 5.77 | 5.7     | 56    |
|                 | Averages | 4.82 | 7.00 | 5.71 | 5.62    |       |
|                 |          |      |      |      |         |       |
| Overall Average |          | 4.59 | 7.02 | 5.58 | 5.58    |       |

**Table 5.** Rainfall pH stats North Ryde NSW Aust 2007 - 2010

Basic observations indicate rainfall pH does vary, not only by the rainfall event but also by the collection container (Table 5).

Further consideration to the change in soil pH was not undertaken but does provide an insight to the changes of soil “solution” pH readings over time. Irrigation water pH should also be regularly measured to determine potential change (eg as in Hydroponic solutions).

Other errors can occur just by the method of sampling (observation). Particularly when the reason of sampling is not defined. An atypical sampling method is to take X (10 – 20) number of smaller soil samples over a ten-centimetre depth. Mix them and send to the lab for analysis. This “result” is an average of all samples over the depth as taken.

But the sampling recommendation do vary (Table 5)

|                      |                          | Soil Samples   |                           |               |           |
|----------------------|--------------------------|----------------|---------------------------|---------------|-----------|
| Company              | Sampling<br>Depth ( cm ) |                | Extractant<br>Phosphorous |               | Potassium |
| Australia            |                          |                |                           |               |           |
| Incitec              | 7.5                      | USA Harris Lab | Colwell                   |               | Colwell   |
| Turfgrass Technology | 7.5                      |                |                           |               |           |
| Chemspray            | 10                       |                |                           |               |           |
| Turforce             | 10                       |                | Bray No 1                 |               |           |
| Pivot                | 10                       |                |                           |               |           |
| US *                 |                          |                |                           |               |           |
|                      | Sampling Depth<br>(cm )  |                |                           |               |           |
|                      | Maintenance              | Established    |                           |               |           |
| Penn State           | 7.6                      | 15.3           | Bray P1                   |               |           |
| Michigan State       | 5.1                      | 5.1            | Bray P1                   |               |           |
| Sewerage Comm.       | 5.1+Thatch               | 15.3 to 20.3   | Hellige-Truog             | Hellige-Truog |           |
| V.P.I.               | 5.1 to 7.6               | 10.2 to 15.3   | Double-Acid               | Double-Acid   |           |
| Maryland             | 7.6                      | 15.3           | "                         |               | "         |
| Rhode Island         | 10.2                     | 15.3           | "                         |               | "         |
| Rutgers              | 15.3 to 17.8             | 15.3 to 17.8   | "                         |               | "         |

**Table 5.** Various sampling recommendations (McKechnie 1997)

An opportunity arose in 2004 to undertake some observation at a Golf Club. The primary object was to define an estimated water holding capacity for each green (too root depth). This included measurements for:

- Root depth
- Organic Matter – Thatch depth
- Water repellancy – Modified water droplet test using pH indicator solution.
- Soil pH over depth.

It was observed that done monthly at hole changing time this would provide positive information over time.

Table 4 indicates soil pH varies across the greens and by depth.

| Green  | Top Dress | OM Depth (cm) | Root Depth (cm) | Dry Patch (cm) | Upper pH | Mid pH | Lower pH | pH Average | Photo   | Effective WHC | MHC | TWHC (mm) |           |
|--------|-----------|---------------|-----------------|----------------|----------|--------|----------|------------|---------|---------------|-----|-----------|-----------|
| 1      | 0         | 4             | 12              | 0              | 6.5      |        | 7        | 6.75       | 14      | 8             | 1   | 8         |           |
| 2      | 0         | 4             | 5               | 0              | 5.5      |        | 6        | 5.75       | 15,16   | 1             | 1   | 1         |           |
| 3      | 0         | 4             | 14              | 0              | 6.5      |        | 7        | 6.75       | 17,18   | 10            | 1   | 10        |           |
| 4      | 0         | 3.5           | 12              | 3              | 6        |        | 7        | 6.5        | 4,5,6   | 8.5           | 1   | 8.5       |           |
| 5      | 0.5       | 3.5           | 9               |                | 6.25     | 6.25   | 6.25     | 6.25       | 7       | 6             | 1   | 6         |           |
| 6      | 0         | 3.5           | 12              | 0              | 6        |        | 6.5      | 6.25       | 8,9     | 8.5           | 1   | 8.5       |           |
| 7      | 0         | 3.5           | 15              |                | 6        |        | 6.5      | 6.25       | 10,11   | 11.5          | 1   | 11.5      |           |
| 8      | 0         | 3.5           | 10              |                | 6.5      |        | 10       | 8.25       | 12,13   | 6.5           | 1   | 6.5       |           |
| 9      | 0.7       | 3.5           | 14              |                | 6        |        | 7        | 6.5        | 3       | 11.2          | 1   | 11.2      |           |
| 10     | 0         | 0             | 0               |                | 6        |        | 6        | 6          | 1       | 0             | 1   | 0         | No Cover  |
| 11     | 0         | 0             | 8               |                | 4        |        | 5        | 4.5        | 2,3     | 8             | 1   | 8         | New Green |
| 12     | 0         | 0             | 15              |                | 4        |        | 5        | 4.5        | 4,5,6,7 | 15            | 1   | 15        | New Green |
| 13     | 0         | 0             | 0               |                | 5.5      |        | 6        | 5.75       | 8       | 0             | 1   | 0         | No Cover  |
| 14     | 0         | 0             | 0               |                | 6.5      |        | 6.5      | 6.5        | 9       | 0             | 1   | 0         | No Cover  |
| 15     | 0         | 5             | 12              |                | 6.5      |        | 5.5      | 6          | 10      | 7             | 1   | 7         |           |
| 16     | 0         | 3.5           | 13              |                | 5.5      |        | 6        | 5.75       | 11      | 9.5           | 1   | 9.5       |           |
| 17     | 0         | 0             | 0               |                | 5.5      |        | 6        | 5.75       | 1,19    | 0             | 1   | 0         | No Cover  |
| 18     | 0         | 2.5           | 20              | 9              | 5.5      |        | 6        | 5.75       | 2,20,21 | 17.5          | 1   | 17.5      |           |
| Putter | 0         | 0.5           | 20              |                | 6        |        | 4.5      | 5.25       | 1,22    | 19.5          | 1   | 19.5      |           |
|        |           |               |                 |                |          |        |          |            |         |               |     |           |           |
|        | Ave Dev   | 1.67          | 5.10            | 2.67           | 0.54     | 0.00   | 0.75     | 0.58       |         | 4.39          |     |           |           |
|        | Median    | 3.50          | 12.00           | 0.00           | 6.00     | 6.25   | 6.00     | 6.00       |         | 8.00          |     |           |           |
|        | Average   | 2.34          | 10.05           | 2.00           | 5.80     | 6.25   | 6.30     | 6.05       |         | 7.77          |     |           |           |

Table 4: Summary of Measurements 11 Dec 2004

Even preliminary observation in some of the Tees (see picture 1 and 2) provided some interesting information.



**Picture 1.** Soil from a Golf Tee (*Cynodon dacylon* spp) pH 8 - 9



Picture 2. Soil in a Golf Tee (*Cynodon dacylon* spp) - pH 4.6 - 5



Picture 3 Soil from a Golf Green (*Agrostis* spp) pH 5.5 top 6.5/7 lower with layered soil water repellence.



Picture 4 Soil from a Golf Green (*Agrostis* spp) pH 5.5/6 with layered soil water repellence zone



Picture 5 Soil from a Golf Green (*Agrostis* spp) pH 5.5-6.5

As we go forward with digital imagery (NDVI etc), monitoring and under laying soil nutrition / soil water conundrum. Soil pH is still useful as a guide as an underlaying layer.

So, what is the “best pH” for your media or soil? This will depend upon your:

- Plant growth observations
- Base soil or media type.
- Measured / recorded regularly
  - Root depth
  - Organic matter depth / percentage
  - Dry or waterlogged
  - Inputs (Fertiliser – Irrigation – Rain – pesticides – etc)
- Management objectives
  - Primary plant health/growth
  - Weed management
  - Diseases disease management
  - Organic matter – content and management
  - Mirco organisms
  - Etc
- Management planning
  - Map layering for decision making (eg GIS, NDVI, Irrigation Uniformity etc)

Soils by their nature are variable by area, depth, and time. Monitoring over continuous time or a minimum two years will provide the general trend of your soil solution pH trends to aim for the drift of pH for the following.

#### 1) Soil Requirement

- |                                     |                           |         |
|-------------------------------------|---------------------------|---------|
| • Mineral (clay/sediment soils)     | pH 5.5 to 6.5 any method  | +/- 0.5 |
| • Organic soils                     | pH 5 to 6 any method      | +/- 0.5 |
| • Inert Soils or Nutrient solutions | pH 5.5 to 6 direct method | +/- 0.5 |

#### 2) Plant Requirement

- See Guideline above
- Mirco pH changes across roots
- Undertake local research

#### 3) Disease Control Requirement

- Anon – Jap 1997.
- Smiley et al. 2005.
- Local research

#### 4) Weed Control Requirement

- Grime et al. 1988
- Undertake local research

#### 5) Irrigation Water or rainfall pH

- Monitoring

Once this is known you can direct your inputs (irrigation water, fertiliser, pesticides, aeolian (particulate and air), topdressing material or organic amendments) to shift the pH in the direction you wish according to your management style.

## References

Annon. 1935. Soil Reaction and Plant Food Availability. The Fertilizer Review. Vol 10. 6 – 7.

Anon – Jap 1997. Guidelines for Non-Chemical Pest Control in Golf Courses. Chiba Prefectural Government, Japan.

Attiwill, P. M. and Leeper, G. W. (1990). Forest Soils and Nutrient Cycles. (Melbourne University Press).

Baas Becking, L. G. M., Kaplan, I. R., and Moore, D. (1960). Limits of the natural environment in terms of pH and oxidation-reduction potential. *Journal of Geology*. **68**: 243 - 284.

Beard, J. B. (1973). Turfgrass: Science and Culture. (Prentice-Hall, Englewood Cliffs, NJ).

Beton Jones Jr. Review of perspective, issues, and trends in soil and plant testing in the United States of America. *Aust. J. Exp. Agri.* 33:L 973 – 81.

Brady, N. C. (1990). 'The Nature and Properties of Soil'. 10th Edition. (Macmillan Publishing Company: New York).

Curry, J.P. 1994. Grassland Invertebrates. Chapman Hall Publishers.

Davies, B. and Howard, D. (1994). Nutritional requirements for promoting browntop in New Zealand Turf. *Proc. 5<sup>th</sup> NZ. Sports Turf Conven.* pp. 59 - 61.

During C. and Mountier, N. S. 1967. Sources of error in advisory tests. III Temporal field Variance. *N. Z. J. Agric. Res.* 10: 134-138.

Grime, J. P., Hodgson, J. G., and Hunt, R. (1988). Comparative plant ecology: A functional Approach to Common British Species. (Unwin Hyman. London).

Handreck and Black. 2002. Growing Media for ornamental plants and turf. 3<sup>rd</sup> Edition UNSW Press.

Koppi, A. J. (1990). Pedology and Land Use. In 'The Scientific Basis of Modern Agriculture'. (Eds. K. O. Campbell and J. W. Bowyer) pp. 79-108. (Sydney University Press in association with Oxford University Press: Australia).

Lindsay. W. 1979. Chemical Equilibria in Soils. The Blackburn Press.

McKechnie 1997. A Study of the Evaluation of Variability in the Turf Environment. Thesis University of Sydney.

Mountier, N. S. and During C. 1966. Sources of error in advisory tests. II Temporal field Variance. N. Z. J. Agric. Res. 9: 964-971.

Mountier, N. S. and During C. 1967. Sources of error in advisory tests. IV Discussion of Total Variance. N. Z. J. Agric. Res. 10: 139-142

Mountier, N. S., Grigg, J.L. and Oomen, G. A.C. 1966. Sources of error in advisory tests. – I. Laboratory Sources. N. Z. J. Agric. Res. 9: 328-338.

Pettinger 1935. A useful Chart For Teaching The Relation of Soil Reaction to The Availability of Plant Nutrients to Crops. [Virginia Agricultural Extension Bulletin 136.pdf \(vt.edu\)](#)

Rayment, G. E. and F. R. Higginson. (1992a). Sampling and Sample Preparation. In 'Australian Laboratory Handbook of Soil and Water Chemical Methods'. pp 7-9. (Inkata Press: Melbourne)

Rayment, G. E. and Higginson, F. R. (1992b). Soil pH. In 'Australian Laboratory Handbook of Soil and Water Chemical Methods'. pp. 17-23. (Inkata Press: Melbourne)

Reid. 1932. The Effects of Soil Reaction Upon the Growth of Several Types of Bent Grasses. USGA Green Selection Bulletin. 12: (5). 196-212.

Rieke, P. E. 1969. Soil pH for Turfgrasses. pg 212-219 1<sup>st</sup> ITRC. Harrogate. England.

Smiley R.W., Dernoeden, P.H, and Clarke, B.B. 2005. Compendium of Turfgrass Disease. 3<sup>rd</sup> Edition. APS Press.

Truog, E. 1947. Soil Reaction Influence on Availability of Plant Nutrients. Agron. J. Vol 11. 305-308

Turner et al 1996. Nutrient Inputs from Rainfall in NSW State Forests. [Nutrient Inputs from Rainfall in NSW State Forests](#) web link

Wild Ed. 1988. Russell's Soil Conditions and Plant Growth.

<http://www.simplyhydro.com/ph.htm>

<http://www.soilandhealth.org/01aglibrary/010143albpap/pH.balanced%20nutrition/pH.bal.nut.htm>