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REVIEW ARTICLE

Soil pH - nutrient relationships: the diagram

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Abstract The pH of the soil in relation to the availability of plant nutrients has been an important research topic in soil fertility and plant nutrition. In the 1930 and 1940 s, a diagram was proposed that showed how the availability of major and minor nutrients was affected by the pH. This conceptual diagram, developed by Emil Truog based on earlier work, included 11 nutrients. The width of the band at any pH value indicated the relative availability of the plant nutrient. The band did not present the actual amount, as that was affected by other factors such as the type of crop, soil and fertilization. For the 11 nutrients on the diagram, a pH of around 6.5 was considered most favorable. The diagram has been often published in text books and soil extension material and continues to be reproduced. This paper reviews how the diagram was developed, and what its limitations are. In recent decades, research in soil fertility and plant nutrition has focused on the biological transformations of plant nutrients in the soil and it has been recognized that the soil pH influences solubility, concentration in soil solution, ionic form, and adsorption and mobility of most plant nutrients. Nutrients interact and different plants respond differently to a change in pH. The soil pH cannot be used to predict or estimate plant nutrient availability, and the diagram should not be used as it suffers from numerous exceptions and barely represents any rules.

Keywords Soil reaction · Acidity · Plant nutrients · Bioavailability · Emil Truog · Soil fertility

> The subject of the relation of soil acidity to the growth of plants is really so complex that it seems almost impossible to get a simple system of classification of economic agricultural plants that may be adapted for general use in this connection. Truog (1918).

Introduction

Acid soils occupy approximately 30% of the terrestrial Earth and are found in humid and subhumid regions. Northern regions that are dominated by cold and temperate climates have acid soils that are classified as Spodosols, Alfisols, Inceptisols and Histosols, whereas in the tropics acid soils are mostly Ultisols and Oxisols (von Uexküll and

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Mutert 1995). Alkaline soils (range of soil orders, but many Aridisols and natric suborders) occur in the western USA, large areas in Argentina, North Africa and the Middle East, and extensive areas in China and Australia (Dregne 1976).

At a global level, there is a pattern between the soil pH and the climate whereby soils with high pH are common in arid areas (Batjes 1995; Simonson 1995) and acid soils are common in many humid and subhumid areas (Hartemink 1998; Sanchez and Salinas 1981). Small changes in water balance cause a steep transition from alkaline to acid soils across climate gradients of the globe (Slessarev et al. 2016). Other factors that affect the soil pH include soil parent material which largely determines mineralogy and soil texture. However, there are also some exceptions to this relationship such as high pH soils in tropical lowlands, and in poorly drained soils of humid regions where carbonates are not leached. Many soils have a pH that is managed through liming (common) or applying acidity (not so common) and in such systems the soil pH is not in equilibrium with its pedoclimatic condition. In parts of the world soils have been acidified following wet deposition of sulfuric and nitric acids from burning of fossil fuels and industrial emissions.

Soil acidity and soil alkalinity in relation to plant growth has been well-studied. The soil pH is often used as an indicator of the chemical fertility of the soil, and it is believed that most major and minor plant nutrients are best available around a slightly acid pH. This concept of soil pH-nutrient availability – the Achilles heel of soil fertility studies - was first developed in the 1930 and 1940 s based on field trials, observation and various assumptions. A soil pH-nutrient availability diagram was developed for the humid regions of the USA that showed the availability of some major and minor nutrients at a pH ranging from 4 to 10 (Pettinger 1936; Truog 1946b). It became known as the "Truog diagram" and it has guided soil fertility research and has been widely reproduced in scientific and popular textbooks. This paper reviews the history and origin of the diagram including its limitations. In another paper we have reviewed the fundamental aspects of soil pH-nutrient relationships (Barrow and Hartemink, submitted).

Emil Truog and soil acidity

Emil Truog was born in 1884 on a farm in the Driftless Area of Wisconsin, USA. His parents had cleared the natural vegetation to grow wheat. At the age of 14, it became clear to Truog that there was no future on the farm, and his teacher suggested that he continued his studies. At home and in the library, he started reading farm magazines that focused on how cropping exhausts soils of lime, phosphorus, and nitrogen. There were articles on the restoration of nitrogen by legumes, and that phosphorus and lime would have to be applied even though those nutrients were returned in the animal manure. In 1905, Truog enrolled in the Agriculture Program at the University of Wisconsin in Madison, USA. He was 21 years old and his father had often told him that production of good crops never failed on new land, but: "…with cropping the luxuriant growth of new virgin land declined rapidly" (Truog 1965).

He studied soil chemistry and learned how to use the litmus paper test for soil acidity and tried the test on the soils of the home farm, but it was unclear whether the soils needed lime or how much was needed. Truog received his BS degree 1909 and a MS in chemistry in 1912 (Lenher and Truog 1916). In 1912, he was hired as an instructor in the Department of Soils at the University of Wisconsin and: "…it was when I began to see how the use of sciences could help solving of the problems of general agriculture, of which I had a first-hand knowledge, that my career in soil science was forged" (Truog 1965). Naturally, he focused his research on the decline in crop production in relation to the depletion of nutrients and how they should be measured and replenished by lime and fertilizers.

Soil acidity, its measurement and remediation became his first topic of research. In the early 1900s, there was considerable research on soil acidity and the emerging concept of pH (Bolt 1997). In 1915, Truog reviewed soil acidity in a paper in *Science*. Some thought acidity was merely caused by organic acids, particularly in peat and muck soils. However, it was noted that there were many well-drained upland soils that were low in organic matter but strongly acid. The question arose: what caused this 'inorganic acidity'? Truog showed that, contrary to the opinion of other authors, it was due to leaching of soluble bases over time and retention of acidity on certain types of silicate clay, such as kaolinite (Truog 1915).

On a more practical level, he aimed to develop a soil pH test that could be an indication for how much lime should be applied. He called an acid soil ‘chronically sick’ and lime was the cure (Truog 1920, 1946a). A litmus paper test for soil acidity was developed whereby moist filter paper collected hydrogen sulfide liberated from a boiling soil suspension (Jackson and Attoe 1971). The filter paper had been soaked in lead acetate, and it was placed over the steam that came from the flask. The paper darkened according to how acid the soil was, which meant more protons, more hydrogen sulfide, and the darker the paper. The color was compared to a paper of known acidity or pH. It stimulated interest in soil tests at a time of diverse opinions about the nature of soil acidity (Truog 1920). He observed that liming was highly beneficial for legume crops like alfalfa as the rhizobia are affected by high acidity and lime improves nodulation. The zinc sulfide test was in use until the 1940s, after which measuring soil pH was done by the glass electrode.

The relationships between soil pH, nutrient availability and the growth of plants was of prime scientific interest to Truog. Although liming of acid soils had been practiced for thousands of years, the scientific basis was not well understood and particularly the relationship between lime and plant growth. He disliked the view that plants were being lime-loving, lime-avoiding or indifferent, or likewise acid-intolerant, acid tolerant or indifferent. It was also realized that soil acidity has numerous direct and indirect influences on soil fertility as it affects the physical, chemical and biological properties of soil (Truog 1918).

The pH-nutrient diagram

In 1936, Nicholas Pettinger from the Virginia Agricultural Experiment Station (USA) published a Bulletin entitled “A useful chart for teaching the relation of soil reaction to the availability of plant nutrients to crops” (Pettinger 1936). He stated that “…the effect of the degree of acidity or alkalinity on the availability of plant foods, or the relation between lime and fertilizers is one of the most widely discussed subjects in agriculture.” Soil reaction was perceived to be “…one of the pulses which indicates the state of health of the soil.” In the bulletin and diagram that came with it, he discussed the range of soil pH in relation to the availabilities of potassium, nitrates, magnesium, calcium, phosphates, iron, aluminium and manganese. A color diagram was presented that composed a series of bands representing the availability of plant nutrients in relation to a pH range of 4 to 10. The changes in width of the bands represents changes in the availability of the nutrient (Fig. 1).

Limitations of the diagram were discussed. It was stated that the diagram was designed to illustrate basic principles in the availability of nutrients in relation to soil reaction, and did not “….portray the situation in a quantitative or absolute manner for any particular soil.” The diagram was considered only valid for well-drained soils of humid regions, and not for alkali soils of arid regions, or poorly drained or

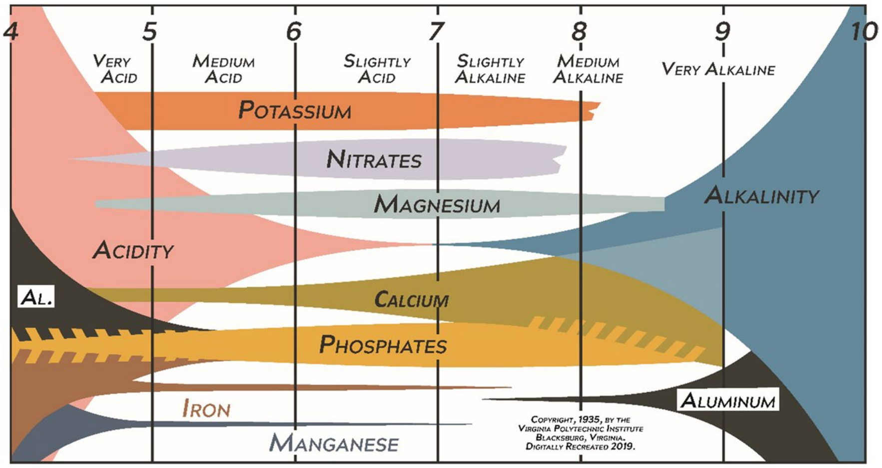

Fig. 1 Diagram illustrating the trend of soil reaction (pH) to the availability of plant nutrients, from “A useful chart for teaching the relation of soil reaction to the availability of plant nutrients to crops” published in 1935 by Nicolas Pettinger

organic soils. He recognized that the availability of some nutrients was directly affected by soil reaction whereas for other nutrients the availability was controlled by processes that were not related to the soil reaction. He also reported that some investigations showed a somewhat different trend. Finally, he noted that "…when the discovery of new evidence makes it necessary to discard present beliefs either wholly or in part, or when better methods of representing the facts are developed, the diagram will be revised and re-issued in improved form" (Pettinger 1936). But that did not happen; he died at the age 34, the same year the diagram was published.

Nicolas Pettinger's bulletin was not widely distributed or recognized but the bulletin was received by Truog who, by the 1930s, had become a national leader in soil fertility and plant nutrition. In the late 1930s, his work on the availability of plant nutrients emphasized that the availability of plant nutrients was a relative matter, and that available should be replaced by 'readily available', and unavailable by 'difficulty or slowly available' (Truog 1937a). He considered the effect of climate whereby lack of water limits plant growth so that lower levels of available nutrients could suffice in soils of dry regions. It became evident that with the same method of chemical analysis, different standards of adequacy of nutrients need to be set up for different climates. Also, different cropping systems and crops have different levels of nutrient requirements and sufficiency levels. In addition to the importance of nutrients in the subsoil, the interdependence of factors besides pH was underscored (Truog 1937a; Truog et al. 1945).

Despite a nuanced and expanding view on nutrient availability, Truog liked the soil pH-nutrient availability diagram of Nicholas Pettinger, and considered it very useful and: "…the subject of tremendous importance in connection with liming, fertilizing, and soil management" (Truog 1946b). He expanded the diagram to 11 nutrients and made it: "…more simple in form but more complete in several aspects" (Truog 1946b). Nitrate and phosphate were replaced by elemental N and P, aluminium was deleted, and sulphur, boron, copper and zinc were added (Fig. 2). The diagram illustrated the relation of the soil pH to plant nutrients in which the width of the band at any pH value indicates the relative availability of the nutrient. The band did not present the actual amount, as that was affected by other factors such as the type of crop, soil and fertilization. For the 11 nutrients on the diagram, a pH of around 6.5 was most favorable, but did not mean a satisfactory supply; it indicated that as far as the soil reaction was concerned, the conditions were favorable. Likewise, it did not mean that outside the favorable range a deficiency would prevail. Nutrients outside the optimal range could be adequately supplied as other factors than the soil pH affected plant growth or as some plants had low requirements

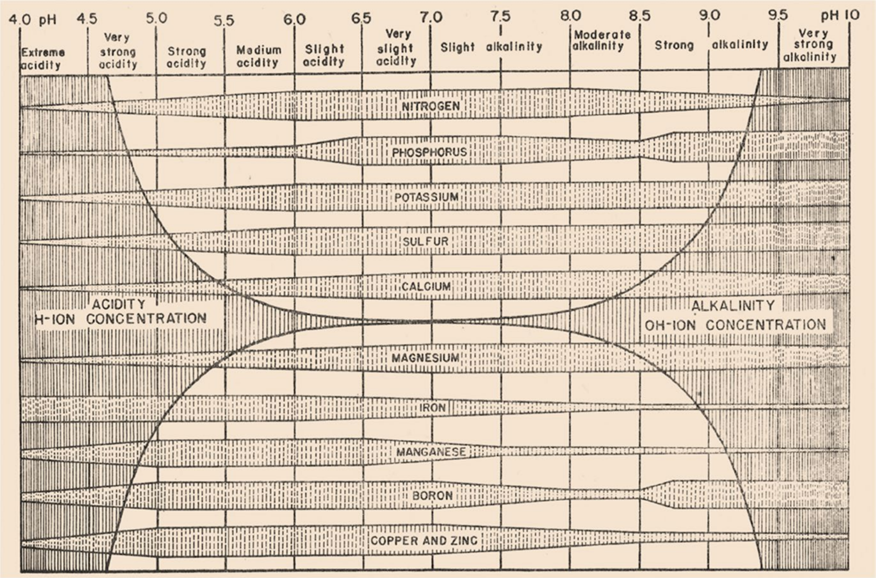

Fig. 2 Much reproduced version of the relationship between soil pH and nutrient availability, from Emil Truog' 1946 paper in the *Soil Science Society of America Proceedings*

for a particular nutrient at a high or low pH (Truog 1946b).

Limitations

The soil pH-nutrient diagram was presented as conceptual in 1937 and 1946, and contained several assumptions. It assumed that the availability of nutrients was the same to all plants in all soils, and that it was best to have the soil around pH 6.5. However, many acid soils are highly productive, as are some soils that have an alkaline pH. The diagram suggested that deficiencies of micronutrients did not occur at low pH and there were no problems with the availability of potassium or sulfur at high pH (Blamey 2005). There are plants that require a high soil acidity such as tea, pineapple (de Geus 1973) blueberry and cranberry, and others that require a high soil pH (often named calcifuge plants).

There are numerous cases in the availability of plant nutrients that do not match the diagram, and some of them were already highlighted by Truog. For example the toxicity of copper and zinc in acid soils (Truog 1918), and the fact that calcium may not be a limiting factor in acid soils (Truog 1918), which is not uncommon (Adcock et al. 2001). It was often found that despite the low availability of calcium at low pH, liming had limited effect as calcium was taken up from the subsoil, other nutrients were limiting (in particular phosphorus), or soil drainage was the problem (Truog 1937b). Improved crop performance with liming is often from the reduction in aluminium toxicity, and calcium deficiency is not always the major cause of poor growth (Blamey and Chapman 1982). Other exceptions to the diagram include, for example, manganese toxicity at low soil pH (Vega et al. 1992), iron toxicity on acid soils (Foy et al. 1979), boron deficiency in alkaline soils (Rashid et al. 1997), and sulfur deficiency on alkaline soils (Russell and Chapman 1988). Some of these exceptions to the pH-nutrient availability concept have been explained as "… simply due to methodology." (Penn and Camberato 2019).

The availability of phosphorus is often assumed to be problematic in low pH soils where it is said to be fixed by iron and aluminium, or in soils with a high pH when phosphorus is precipitated by calcium. Of all the plant nutrients this is probably the most widely accepted pH-availability relationship, and in a recent review it has been termed the "… the classic understanding of the effect of pH on P uptake from soils" (Penn and Camberato 2019). Barrow recently summed up the problems with this model: it makes wrong predictions, there is very little evidence for the existence of the separate postulated sinks for phosphate, and it has no facility for explaining other aspects of the behaviour of phosphates (Barrow 2017). There are different effects of pH on the P availability. When the pH is decreased from 6 to 4, the rate of uptake of phosphate by roots increases, the amount desorbed from soil increases, and the amount sorbed by soil often also increases. The first two increase the P availability; the third effect decreases it. The pH-phosphorus availability diagram fails the most fundamental test of science and is difficult to understand why it persists (Barrow 2017),

Soil pH is a useful indicator of the soil condition and it affects numerous soil chemical reactions and processes (Sparks 2003). But it cannot be used to predict or estimate plant nutrient availability and different plants respond differently (Clárk 1983; Marek and Richardson 2020) as nutrients interact which can be synergistic as well as antagonistic (Dhaliwal et al. 2022). Soil pH influences solubility, concentration in soil solution, ionic form, and mobility of most plant nutrients. Soil pH affects the availability of many nutrients but the optimum pH for plant growth depends on which nutrient is the most limiting (Barrow 2017). Furthermore, the activity of microbial communities and a range of chemical reactions in soil are affected by fluctuating pH. The bulk pH of the soil (commonly measured in a soil-water ratio) may not reflect the pH in the rhizosphere where nutrients are taken up by the plant. The soil solution pH is relevant for soil and plant biogeochemical processes, and better a predictor of crop yields than the soil pH measured in a soil-water mixture (Moody et al. 1998).

Another electrochemical phenomena related to the pH is soil redox potential which is measured by pE (the negative logarithm of the free-electron activity) and related to oxic, sub-oxic or anoxic soil conditions. Large pE values cause electron-poor or oxidized species whereas large values of the pH yield the bases or species low in protons (Sposito 1989). Combining a pE and pH diagram allows for the prediction of the redox species at equilibrium under oxic, suboxic, or anoxic soil conditions. The influence of soil pH on bioavailability is indirect at best, through the competition with cations for dissolved ligands or surface functional groups, and through breaking-down of minerals by the protons which may enhance the bioavailability of some metals. There is also a direct effect of acidity on plant roots and on soil micro-organisms (Sparks 2003; Sposito 1989), and pH at the root surface may differ from that of the bulk soil (Barrow 2017). Some recent research highlighted the importance of root-induced changes in the rhizosphere pH. In soils with pH-dependent charge (e.g. Ultisols, Oxisols), pH increases tend to increase the P concentration in solution and its availability to plants, whereas in soils with permanent charge it is typically the other way around (Kuppe et al. 2022).

Discussion

Emil Truog believed that the soil pH – nutrient availability diagram presented a fairly reliable picture, but he stressed that it was generalized and tentative and partly based on assumptions as data were lacking. The 1946 paper on "Soil reaction influence on availability of plant nutrients" provided no data and no references, and stands prominently amongst Truog's scientific legacy (Hartemink 2021). The diagram has never received further investigation but ended up in many text books and popular soil books such as *Our Garden Soils*, the book by Charles Kellogg that aimed to educate gardeners about soil (Kellogg 1952). The diagram continues to be used in textbooks and encyclopedia and numerous papers (e.g., Brady and Weil 2008; Fernández-Martínez et al. 2019; Fine et al. 2017; Larcher 2001; McGrath et al. 2014). According to Google Scholar, Truog's paper on the effect of acidity on of soil nutrient availability has 146 citations (Truog 1946b) but his diagram has many more usages – often without citation which suggests that it has been accepted as common knowledge. It has become a defining principle in soil fertility and plant nutrition.

Since the 1950s, a large amount of research work has been done on the solubility of nutrients, the biological transformations of nutrients in soils, and the effect of soil pH on adsorption and plant uptake. None of that can possibly be summarized in a simple diagram. The relationship between soil pH and nutrient availability remains of interest as nutrient availability in acid and alkaline soils is unique for each soil, crop and climatic region. Many soils experience land-use and climate change that causes changes in the water balance (Slessarev et al. 2016), which impacts nutrient bio-availability at a changing soil reaction.

References

Adcock KG, Gartrell JW, Brennan RF (2001) Calcium deficiency of wheat grown in acidic sandy soil from Southwestern Australia. J Plant Nutr 24(8):1217–1227

Barrow NJ (2017) The effects of pH on phosphate uptake from the soil. Plant Soil 410(1):401–410

Batjes NH (1995) A global dataset of soil pH properties. ISRIC, Wageningen

Blamey FPC (2005) Comments on a figure in "Australian soils and landscapes. An Illustrated Compendium". ASSSI Newsletter, p 142

Blamey FPC, Chapman J (1982) Soil amelioration effects on peanut growth, yield and quality. Plant Soil 65(3):319–334

Bolt GH (1997) Soil pH, an early diagnostic tool: its determination and interpretation. In: Yaalon DH, Berkowicz S (eds) History of soil science international perspectives. Advances in geoecology. Catena Verlag, Reiskirchen/Germany, pp 177–210

Brady NC, Weil RR (2008) The nature and properties of soils, 14th edn. Pearson-Prentice Hall, Upper Saddle River

Clárk RB (1983) Plant genotype differences in the uptake, translocation, accumulation, and use of mineral elements required for plant growth. Plant Soil 72(2–3):175–196

de Geus JG (1973) Fertilizer guide for the tropics and subtropics. Centre d'Etude de l'Azote, Zurich

Dhaliwal SS, Sharma V, Shukla AK (2022) Chapter one - impact of micronutrients in mitigation of abiotic stresses in soils and plants—A progressive step toward crop security and nutritional quality. In: Sparks DL (ed) Advances in Agronomy. Academic, pp 1–78

Dregne HE (1976) Soils of arid regions. Developments in soil science no. 6. Elsevier, Amsterdam

Fernández-Martínez M, Sardans J, Chevallier F, Ciais P, Obersteiner M, Vicca S, Canadell JG, Bastos A, Friedlingstein P, Sitch S, Piao SL, Janssens IA, Peñuelas J (2019) Global trends in carbon sinks and their relationships with CO2 and temperature. Nat Clim Change 9(1):73–79

Fine AK, van Es H, Schindelbeck R (2017) Statistics, scoring functions, and regional analysis of a comprehensive soil health database. Soil Sci Soc Am J 81:589–601

Foy CD, Oakes AJ, Schwartz JW (1979) Adaptation of some introduced eragrostis species to calcareous soil and acid mine spoil. Commun Soil Sci Plant Anal 10(6):953–968

Hartemink AE (1998) Acidification and pH buffering capacity of alluvial soils under sugarcane. Exp Agric 34(2):231–243

Hartemink AE (2021) Soil Science Americana - chronicles and progressions 1860–1960. Springer, Dordrecht

Jackson ML, Attoe OJ (1971) Memoriam Emil Truog 1884–1969. Soil Sci 112:379–380

Kellogg CE (1952) Our garden soils. The MacMIllan Company, New York

Kuppe CW, Kirk GJD, Wissuwa M, Postma JA (2022) Rice increases phosphorus uptake in strongly sorbing soils by intra-root facilitation. Plant Cell Environ 45(3):884–899

Larcher W (2001) Physiological plant ecology. Springer-Verlag, Berlin-Heidelberg

Lenher V, Truog E (1916) The quantitative determination of silica. J Am Chem Soc 38:1050–1063

Marek RS, Richardson JB (2020) Investigating surficial geologic controls on soil properties, inorganic nutrient uptake, and northern hardwood growth in Western Massachusetts, USA. J Soil Sci Plant Nutr 20(3):901–911

McGrath JM, Spargo J, Penn CJ (2014) Soil fertility and plant nutrition. In: van Alfen N (ed) Encyclopedia of Agriculture and Food Systems, vol 5. Elsevier, San Diego, pp 166–184

Moody PW, Aitken RL, Dickson T (1998) Field amelioration of acidic soils in south-east Queensland. III. Relationships of maize yield response to lime and unamended soil properties. Aust J Agric Res 49(4):649–656

Penn CJ, Camberato JJ (2019) A critical review on soil chemical processes that control how Soil pH affects phosphorus availability to plants. Agriculture 9(6):120

Pettinger NA (1936) A useful chart for teaching the relation of soil reaction to the availability of plant nutrients to crops. Virginia Agricultural and Mechanical College and Polytechnic Institute and the United States Department of Agriculture, Cooperating, Blacksburg

Rashid A, Rafique E, Bughio N (1997) Micronutrient deficiencies in rainfed calcareous soils of pakistan. III. Boron nutrition of sorghum. Commun Soil Sci Plant Anal 28(6–8):441–454

Russell JS, Chapman AL (1988) Sulfur deficiency in rice grown on the alkaline soils of the ord irrigation area, western australia. Aust J Exp Agric 28(1):111–117

Sanchez PA, Salinas JG (1981) Low-input technology for managing oxisols and ultisols in tropical America. Adv Agron 34:279–406

Simonson RW (1995) Airborne dust and its significance to soils. Geoderma 65(1–2):1–43

Slessarev EW, Lin Y, Bingham NL, Johnson JE, Dai Y, Schimel JP, Chadwick OA (2016) Water balance creates a threshold in soil pH at the global scale. Nature 540(7634):567–569

Sparks DL (2003) Environmental soil chemistry, 2nd edn. Academic, Amsterdam

Sposito G (1989) The chemistry of soils. Oxford University Press, New York

Truog E (1915) Soil acidity and methods for its detection. Science 42:505–507

Truog E (1918) Soil acidity: I. Relation to growth of plants. Soil Science V:169–195

Truog E (1920) Testing soils for acidity. Bulletin. Agricultural Experiment Station, University of Wisconsin, Madison, p 24

Truog E (1937a) Availability of essential soil elements - a relative matter. Soil Sci Soc Am Proc (1):135–142

Truog E (1937b) A new soil acidity test for field purposes. Soil Sci Soc Am Proc 1:155–159

Truog E (1946a) Andrew Robeson Whitson 1870–1945. Soil Sci 60:272–274

Truog E (1946b) Soil reaction influence on availability of plant nutrients. Soil Sci Soc Am Proc 11:305–308

Truog E (1965) Reflections of a professor of soil science. Soil Sci 99:143–146

Truog E, Attoe O, Jackson M (1945) Fertilizer application rationalized. Soil Sci Soc Am Proc 10:219–223

Vega S, Calisay M, Hue NV (1992) Manganese toxicity in cowpea as affected by soil pH and sewage sludge amendments. J Plant Nutr 15(2):219–231

von Uexküll HR, Mutert E (1995) Global extent, development and economic impact of acid soils. Plant Soil 171(1):1–15

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