The Fundamentals of Soil Nutrient Management, Soil Testing and Fertiliser Recommendations

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Dr Charles N Merfield

The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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1. Introduction

Soil management is topic of increasing interest among farmers, growers and the world at large, as evidenced by the Food and Agriculture Organisation (FAO) of the United Nations (UN) declaring 2015 to the 'International Year of Soils'. This is being driven by a wide range of issues, from practical farming concerns such as improving productivity, all the way through to global issues such as soil degradation and the linkage between soil and climate change. Improving soil quality / health is therefore every bodies business.

However, coupled with this growing interest in soil quality, there feels like there is an equivalent increase in the confusion about how best to manage soil. For example, there is a growing plethora of 'biological' / 'organic' fertilisers (i.e., as opposed to mineral / inorganic fertilisers), along with a growing array of soil testing approached and laboratories, all claiming to be able to help farmers and growers improve their soils and/or their bottom lines.

The purpose of this article is to sort the wheat from the chaff and explain the role of 'chemical' soil tests within an overall soil management plan including fertiliser recommendations, managing soil organic matter and soil biology.

2. What and why are soil tests, testing for?

All physical things in the universe, including everything here on earth are made up of the 92 naturally occurring chemical elements, ranging from hydrogen to uranium. Living things, e.g. plants and animals are made of only 19 elements, give or take one or two depending on the life form. These are called the 'essential' elements of life, meaning that even if all the other elements are present, if one of these elements is missing, then the organism will die.

2.1. Essential nutrients

Using plants as an example as they are the start of the food chain, living things use of the chemical elements is very skewed: not only does life use only 19 out of the 92 chemicals elements, the proportions of those 19 is also very lopsided. Table 1 shows the typical proportion of the chemical elements in plants, which shows that between them, carbon, oxygen and hydrogen make up 96% of plants as dry weight (as wet weight they are about 95% H_2O).

Table 1. Proportion of nutrients in plants.

Element	Percent	Element	Percent
Carbon	45	Sulphur	0.1
Oxygen	45	Iron	0.01
Hydrogen	6.0	Chlorine	0.01
Nitrogen	1.5	Manganese	0.005
Potassium	1.0	Boron	0.002
Calcium	0.5	Zinc	0.002
Phosphorus	0.2	Copper	0.001
Magnesium	0.2	Molybdenum	0.00001

This proportion is a zero sum game. If there is a larger proportion of one element, then one or more other elements must logically have a reduced proportion. After carbon, oxygen and hydrogen, which can be considered the 'general scaffold' out of which life is built, all the other elements have quite specific functions. For example, nitrogen is what makes a protein a protein and iron is at the heart of the haemoglobin molecule that carries oxygen in animals blood. It therefore logically follows from this, i.e., indisputably, that if the proportions of the elements within an organism vary too far from optimum, then, there is going to be trouble.

In many ways that is not news: most people know that if they don't eat a 'balanced diet' then they will get sick, due to a nutrient (i.e., chemical element) deficiency or excess, and if the imbalance is sufficiently severe, then some very unpleasant health effects will occur, including death.

This equally applies to livestock - if the pasture they are eating does not contain sufficient amounts of the nutrients they need also in the right proportions they will not thrive, or worse, become sick. Therefore the information in this booklet is just as applicable to livestock, and it is clearly directly applicable to pasture management.

So what does this mean for soil testing? Well, plants are the foundation of the food chain, and apart from carbon and oxygen that plants get straight out of the air (i.e., they are atmospheric fertilisers), they absorb all the other nutrients they need from the soil (the lithospheric fertilisers). So, if the soil is deficient in one or more nutrients, then the plants are not going to be able to take up enough of those nutrients to grow, or grow as well as they could. This is the fundamental point of soil testing: i.e., to determine if there are sufficient levels of the essential elements for plants to grow at their best.

However, things get a bit more complicated as we move from the idealised world of physics into the much more convoluted real world of chemistry and biology.

2.2. Liebig's 'Law of the Minimum'

First up there is the need to have sufficient amounts of all the elements available from the soil, i.e., in the right proportion. This is where Justus von Liebig's famous 'Law of the Minimum' and his barrel metaphor (Figure 1) comes in.

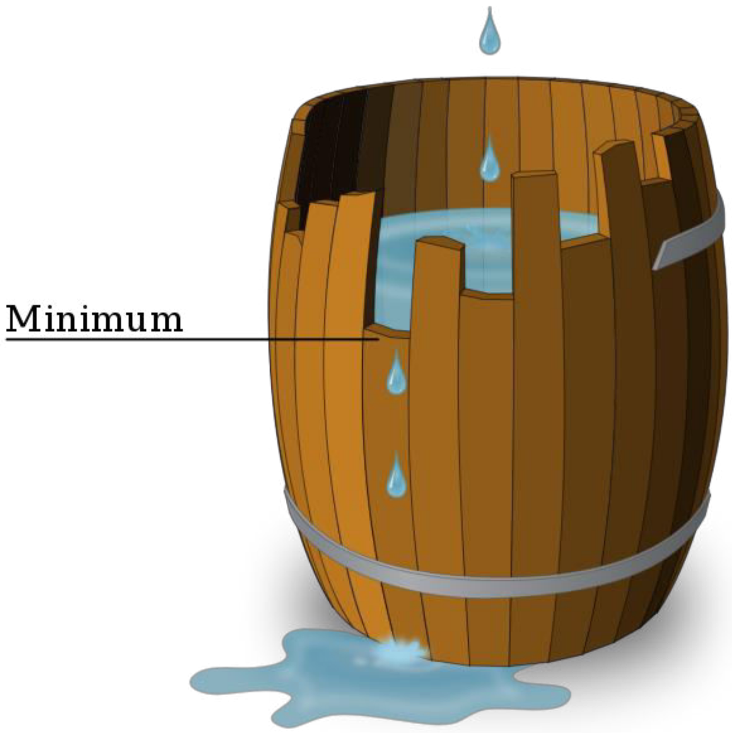

Figure 1. Liebig's barrel (from http://en.wikipedia.org/wiki/File:Minimum-Tonne.svg).

The idea of Liebig's barrel, is that yield is dictated by the most limiting nutrient, depicted as the shortest stave, which determines the height of water in the barrel (the yield). This has been the foundation of soil fertility and fertiliser application for over a century, and it is still a useful starting point, however, it is a bit of a simplification.

Stepping back, to the concept of needing the correct proportions of a nutrient (discussed above), it is clear that an excess as well as insufficient nutrient levels will effect yield (or any other measure of crop performance we care to use, e.g., quality, flavour, disease resistance, etc.), due to an excess of one nutrient meaning that one or more of the other nutrients has to be reduced, i.e., the height of the staves in the barrel are interdependent, if one goes up, one or more, must go down to compensate.

2.3. Yield curves - the full story

Again, as much as by logical deduction, as by empirical evidence, (i.e., this is utterly solid ground) this means that all nutrients have a bell shaped curve in terms of the availability to the plant of a nutrient and its performance (growth, yield etc.,) as shown in Figure 2.

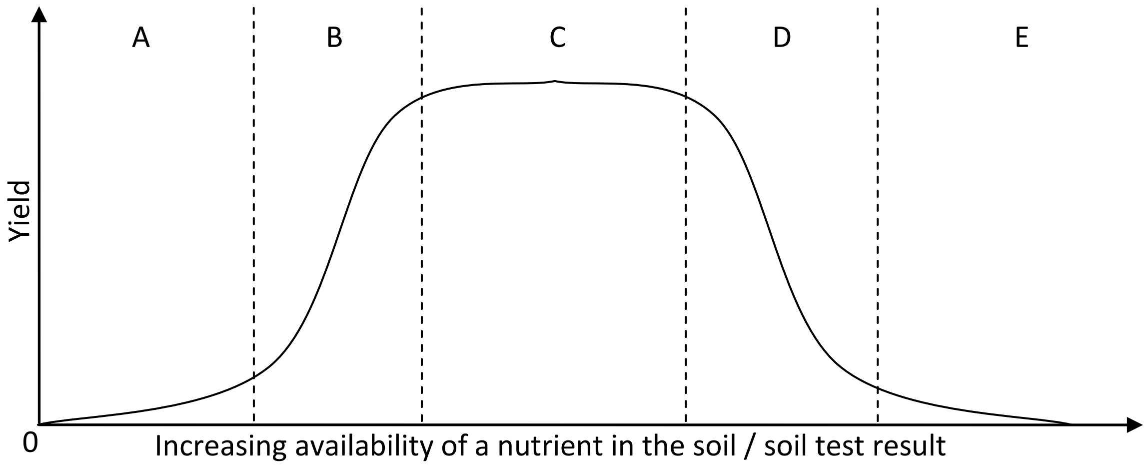

Figure 2. The bell shaped curve of yield (or other plant response) against the amount of one nutrient / chemical element in the soil.

These yield curves, visually show how much a plant will yield depending on how much of a particular nutrient is available to it in the soil. For example, if there is only a small amount of available nutrient, plants will yield poorly, if there is a good amount, plants yield well.

Yield curves should really be called ‘plant growth response curves’ or ‘crop growth response curves’ as yield is not the only measure of plant performance (see section 3.5). However, plant growth response curve is rather a mouthful and yield curve is the more common term.

First, in most discussions of nutrients, only the left side of the yield curve is presented, i.e., to the middle of section C, which gives an S shaped (sigmoid) curve. However, that is only half of the story: there are in fact five major divisions within a yield curve.

When there is zero available amount of an essential element, then the plant can’t grow, full stop, so there is no plant (the starting point of the curve in section A) and ipso facto, zero yield. As the amount of nutrient increases, the plant can start to function, but only just, as it is still severely deficient in that nutrient, and it therefore functions so poorly that it only has a slow growth response to increasing nutrient levels as represented by section A, where the curve is nearly flat. In the field, this means that adding a lot of fertiliser produces very little response, so some people take this to mean the fertiliser is not working, which is clearly not the case.

As the nutrient level increases further, a tipping point is reached (the inflection point or ‘bend’ in the curve and start of section B), where the plant now has enough of the nutrient to start growing well, and each extra unit of nutrient allows the plant to grow much better. This is represented by section B where the curve grows exponentially, and corresponds to the field situation where a little fertiliser produces a huge crop response and people can be lead to believe that they have found a miracle fertiliser. This is also clearly not the case, because if they keep adding their 'miracle' fertiliser they will reach the second inflection point where the curve levels off again, represented by section C.

Section C represents the satiated point of plant growth: this is where the plant has reached its maximum performance as determined by the nutrient in question and adding more nutrient produces no response. In the field, this is seen as a crop completely failing to respond to fertiliser, and the person using it, thinking the fertiliser has failed to work and is therefore a complete dud, i.e., the opposite of a miracle. Once again this is not the case.

This is the point that most soil nutrient commentaries stop, and show only an sigmoid curve, but, there is still more to come. Just as section C represents the point where adding fertiliser produces no response, there is also a point where adding more fertiliser, produces a negative response, as represented by section D. This is where the zero sum game of the proportion of nutrients in crops starts rear its ugly side. If there is too much of one nutrient available, and the plant takes this up, it logically means that another nutrient or nutrients are going to be 'pushed out' (see also section 5.3). If the forced reduction of those other nutrients then means that the plant can't perform as well, then yield will start to decline. In other cases, especially in the micro-nutrients, excess of a nutrient can be directly toxic to the plant. What therefore happens in the field, is that adding fertiliser causes a decrease in yield, so the aggrieved producer then heads off to the fertiliser supplier wanting their money back! Again based on a false understanding.

The final point is section E where there is so much nutrient available the plant ends up dying. This is not just caused by inorganic / mineral fertilisers, but also by sufficiently concentrated biological / organic fertilisers, as shown in Figure 3 where some fish based fertiliser has been spilled on pasture killing it very effectively (NB, this does not mean that such products can be used as herbicides, as the amount required per hectare would be uneconomic, and, also because of the damage caused to the soil and future crops from excess nutrients).

Figure 3. Pasture killed by a spill of organically certified fish based fertiliser.

2.4. What yield curves tell us and how fertiliser recommendations are made

To reiterate, yield curves can be logically deduced from the facts that plants (and all living things) are made of chemical elements and that those elements have to be within a pretty narrow range of proportions for the organism to be healthy. This means that this is exceptionally reliable knowledge on which to build an understanding of soil testing and fertilisers.

The next reiteration is that the bell shaped curve highlights the first over-simplification of Liebig's barrel in that the lengths of the staves are all dependent on each other, i.e., they have to 'add up' to 100%, if the height of one stave goes up, it will force other staves to go down, which may result in the water level, i.e., plant yield, dropping.

The bell curve also kills the misbelief that it is fertilisers that make a crop grow, rather it is the amount of available nutrients provided by both soil reserves and applied fertiliser that determine plant growth. That is why adding fertiliser (in any form mineral or biological) can result in little crop response (sections A, C and E) and a large positive (section B) and negative (section D) responses. So next time someone tells you they have a miracle fertiliser, or their product will increase yield by X%, you know to turn and walk away, as they either don't know what they are talking about, or worse, they are snake oil salesmen.

Finally, it is yield curves that are at the heart of fertiliser recommendations. The soil test measures the amount of each nutrient in the soil; the yield curve indicates if the level of nutrient found in the soil test is sufficient to produce the optimum yield. If the soil level is not sufficient, then the curve shows how much more nutrient needs to be added to the soil to achieve maximum yield, for example in Figure 4 the left hand vertical dashed line indicate the soil test result / soil nutrient level, while the right hand dashed line is the optimum level of soil nutrient, i.e., that gives the maximum yield, so the distance between the two lines is the amount of extra nutrient that has to be applied to achieve maximum yield. The amount of extra nutrient required has to be further converted into a fertiliser recommendation as few nutrients are applied in elemental form (except sulphur) and other factors need to be taken into account, e.g., the rate of release, economic return, etc., to give the amount of fertiliser that has to be applied.

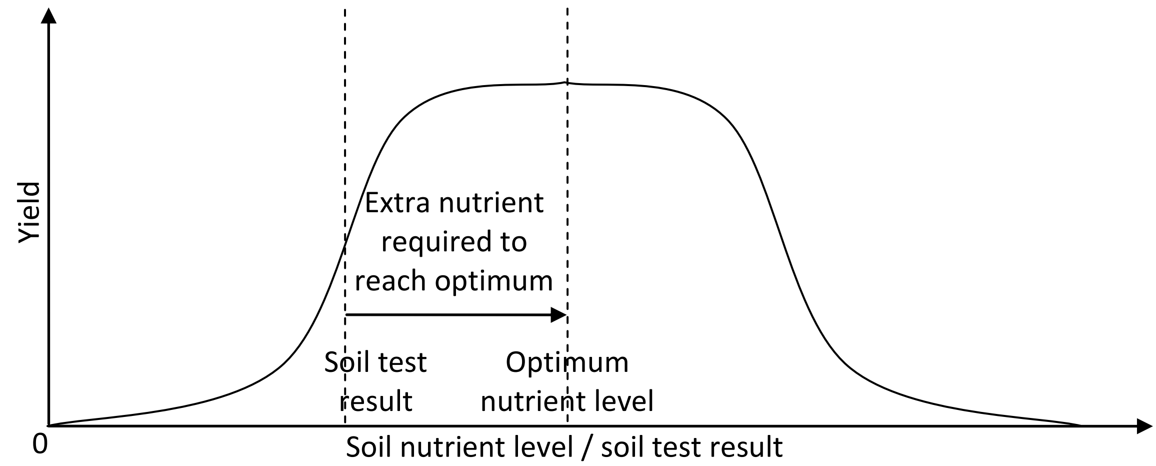

Figure 4. How yield curves are used to determine fertiliser recommendations.

So, at its core, soil testing and fertiliser recommendations are really quite simple, however, surrounding this central simplicity, are many layers of complexity, rather like a Russian nesting doll.

3. Chemical soil tests: A simulation, based on an approximation, informing an empirical estimate, wrapped up in a value judgement!

The thin, crisp, lines of yield curves, (such as Figure 2) and the apparently hard and fast numbers on soil test reports, belie considerable complexity and ambiguity. This means that soil tests results are not as 'precise'[1] as the hard numbers and crisp yield curves make them appear to be. In fact soil tests and their results are based on a stack of issues that mean they contain much greater latitude than is commonly understood. To paraphrase Churchill, soils tests can be considered to be an a **simulation** based on an **approximation**, informing an **empirical estimate** all wrapped up in a **value judgement**.

3.1. The science of the limits of soil tests

As explained in section 5.2, plants can only take up nutrients in a very limited range of inorganic / mineral forms, so, while the soil as a whole can contain prodigious amounts of any given nutrient, mainly in the form of rock particles, the amount of available nutrients is often very small. For example, the amount of plant available phosphorus per hectare may be only a few hundred grams, while there could be two tonnes of total P per ha within the plough layer. Soil tests therefore need to determine the amount of plant available nutrients, rather than the total amount, as it is only the plant available forms that make plants grow, as the rest are of no value to them, and adding any amount of the unavailable forms, will, by definition, have zero effect on plant growth.

3.2. A simulation

However, while determining the total elemental composition of soil is easy with modern analytical machinery, estimating the amount of plant available elements / nutrients requires that the test '**simulates'** a plants ability to absorb each nutrient. As further explained in section 5.2, nutrient uptake is not a simple process, rather complex biological mechanisms are required. Simulating these complex biological mechanisms by chemical reactions in the proverbial 'test tube', i.e., a chemical soil test, is a pretty tall order. That soil chemists have developed a large range of tests that can chemically 'simulate' complex plant biology, is therefore very impressive.

However, while chemical soil tests can achieve a good simulation of plants ability to take up nutrients, they are not perfect. For starters, not all plants take up nutrients equally effectively and uptake can also be affected, sometimes dramatically, by a considerable range of factors such as pH and mycorrhizal associations. For example, Figure 5, shows two very different yield curves to phosphorus depending on whether the plant had or did not have a mycorrhizal association.

[1] Precise and accurate are two different but related terms: accurate means a measurement is close to a quantity's actual / true value while precision refers to the repeatability, or reproducibility of the measurement having similar values, see http://en.wikipedia.org/wiki/Accuracy_and_precision

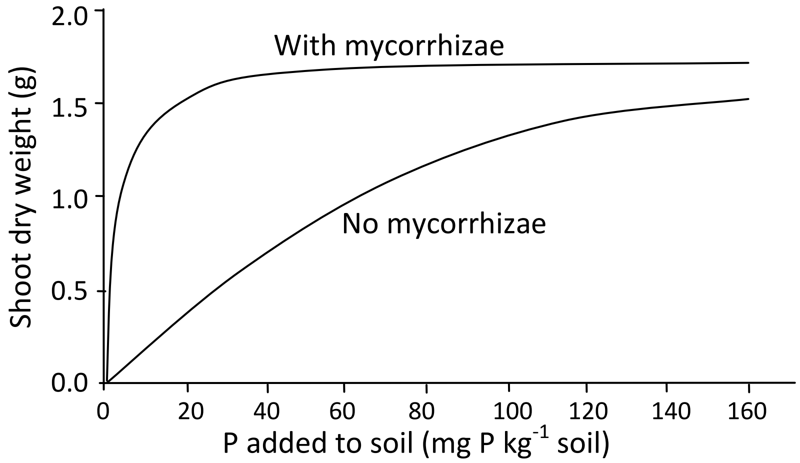

Figure 5. Two contrasting plant yield curves, across a range of soil phosphorus levels with and without mycorrhizal association.

It is simply impossible to have a single chemical soil test that will produce different results according to whether the crop the test is being conducted for, has a mycorrhizal association or not, that would require two different tests. And, even if the chemical tests could accurately simulate one plant species, they simply cannot accurately simulate them all, nor the wide range of other factors that influence a plant's response to nutrient levels, such as pH.

The results of chemical tests are therefore an estimate / guide to the amount of plant available nutrients in your soil, available to your crop, under your climate. Soil test results are therefore, definitely not definite- they have to be 'converted to produce fertiliser recommendations for a given soil and crop.

3.3. An approximation

Next, the **approximation** refers to the sample of soil sent to the lab to be tested. In one hectare, there is about 7,500 tonnes of soil in the plough layer (30 cm). A typical soil sample collected from several if not several tens of hectares of farmland may only be 2–400 grams, and of that, only 50 g or less may be used in an individual soil test. The amount of soil actually tested therefore represents about 0.0000007% of the plough layer in one hectare, and a lot less again for more than 1 ha. This is clearly a very substantial **approximation**, especially considering the huge variability of soils over small distances in many countries.

For this approximation to be representative, it is vital that fields are correctly sampled. Indeed, the most important part of a soil test in terms of ensuring both its accuracy and precision, is the field sampling, not the lab tests. That is why it is so vital to get as representative sample as possible by taking sub-samples from all over the field or fields, typically using the well known 'W' sampling pattern. The more samples that you take, the more accurate and precise your soil results will be. Therefore, the one thing you should, never, ever, skimp on, is spending time taking a representative sample of soil for testing.

However, regardless of how well you sample your field, the sample you send to the lab can only ever be an approximation of the sampled area. The corollary of this, is that even if you have a good representative sample (a good average) of the whole field, but there is variability within the field (and globally there are very few fields that are really homogenous as yield maps clearly show) then the sample is going to be different to those different parts of the field. So, the sample is at best an approximate of the average of the entire field and the different parts of the field will vary from the sample. This issue is a key driver behind precision agriculture[2].

3.4. Empirical estimates

As explained in section 3.2 above, chemical soil tests can 'only' provide a general measure of the amount of available plant nutrients in a sample of soil. However, plants vary, often considerably, in how well they can absorb different nutrients, and also how much they need, and therefore how they respond to different levels of soil nutrients. For example, grasses with their filamentous roots are more effective at absorbing nutrients from soil that the dicots with their thicker tap root systems; and carrots and other root vegetables (and weeds such as dock) that have a storage (tap) root, need more potassium than leaf crops, e.g. lettuce, because root crops need potassium to move nutrients from the leaves to the roots. Therefore the general measure of available soil nutrients provided by chemical soil tests have to be 'converted' into an individually tailored recommendation for individual crops.

Plants / crops are not the only variable in soil testing; soils are inherently variable as well. Even though the chemical soil test simulates the amount of available plant nutrients within the individual soil sample, factors, such as soil texture (i.e., proportion of sand, silt and clay) and the cation exchange capacity can influence the crops response to a given test result. For example, some soils lock up practically all applied phosphorus, while others rapidly serve it up to plants, and some hang on to any applied nitrogen, while for others it near drains straight through, so the fertiliser recommendations have to take such factors into account when working out how much nutrient to apply, for a given soil, based on the test results.

The solution to the above issues is the use of lookup tables that predict how individual plant species will respond to adding nutrients for any given nutrient level across a range of different soil types, i.e., yield curves.

The really big problem with this is, there is no, repeat, **no**, means of working out a crop's response to a given amount of nutrients, as fertiliser, manure, compost, etc., on any given soil type, other than growing a crop and seeing what happens. In scientific jargon, this is called **empirical**, i.e. the opposite of theoretical. To put it another way, the precise numbers given on soil tests / fertiliser recommendations can give the false impression that someone has calculated, based on some kind of fancy formula that has been worked out theoretically, how much fertiliser to apply, e.g. like an engineer or physicist can pretty much calculate everything from theory alone. However, there is no chance of doing this in biology. Biology is much, much harder than physics and engineering, and it is simply impossible to calculate most things in biology from first principles. Calculating the three way interaction between a crop plant, the soil it is growing in and the weather it experiences is just mind bogglingly complex: it makes modelling climate change the equivalent of adding up shopping. In short, it is utterly impossible to calculate yield curves from theory, they can only be determined empirically, i.e., by growing real crops in real fields with a range of soil nutrient levels, adding different amounts of nutrients and recording the results.

Considering the wide range of soil types, crops and initial soil nutrient levels this is clearly a pretty big matrix of crop and soil combinations, and as the responses can only be worked out by undertaking replicated randomised field trials, a clearly mind boggling number of field trials number of field trials is required to test every possible combination of crop type, soil, nutrient level, fertiliser type, etc. To get over this impossibility, soil chemists, mainly many decades ago, spent a lot of time conducting a range of representative tests, e.g. using one crop species as a stand-in for a bunch of similar crops,

[2] http://en.wikipedia.org/wiki/Precision_agriculture

and using a small range of soil types as representatives of all soil types, and specific fertilisers as stand in for all the different fertilisers, and then filled in the gaps with calculated **estimates**. And to be fair to them, they did a really good job, but, despite that, it is impossible to bypass the fact that crop response to fertiliser has been, and can only be, determined by **empirical** trials with the gaps **estimated** by extrapolation. There is clearly wriggle room in this, and it is already sitting atop both a simulation and approximation.

To summarise, the apparently precise numbers on soil test results, and especially the resulting fertiliser / nutrient recommendations, are no where near as hard and fast as they appear.

3.5. A value judgement

Finally to cap things off, the **simulation** that is based on an **approximation**, which in turn informs an empirical **estimate** are themselves wrapped up in a **value judgement**. Value judgements, i.e., matters of what is right and wrong, are outside the remit of science, as is impossible to design an experiment to tell you if something is right or wrong, e.g. if stealing is right or wrong. Science and the scientific method can only tell if something is true or false (or to be accurate, the probability that it is not false). Values are part of ethics and morals, i.e. what people consider to be good or bad, right or wrong. As science is mute on the issue of values, choosing among different value systems is therefore the job of citizens not scientists. Unfortunately, a lot of people don't (consciously) understand this, including a lot of scientists including many agricultural scientists. This error even has a formal name 'scientism'[3]. What, therefore, has scientism got do to with soil testing?

It is widely considered that maximising yield is a scientific objective. This is the idea that underpins the Green Revolution and most of main-stream agriculture (along with maximising profit). However, this is wholly incorrect. It is impossible to design an experiment to show that maximising yield is correct. Conversely, it is entirely possible to design experiments of **how** to maximise yield (of which there are many millions, as maximising yield has been the dominant focus of agricultural science for over a century) however no experiment can determine that maximising yield is the morally right thing to do. This is because maximising yield is a value judgement. At the most fundamental level, this is what separates organic from industrial agriculture: industrial agriculture is based on the value / ethic of maximising yield and/or profit; organic agriculture on the value / ethic of maximising sustainability. So, what do values have to do with soil testing?

The sole objective / ethical value underlying soil tests is yield maximisation. However, maximising yield is only one of may possible objectives for agriculture, as attested by organic agriculture with its values of sustainability. It would be equally valid to have an soil testing objective of maximising crops nutritional quality, or pests & disease resistance, or flavour, or lots of other objectives, including having multiple objectives. This is why soil testing is **wrapped up in a value judgement:** if a different value judgement was used as the objective for soil testing, then the recommendations on how much nutrients to apply may well be different.

So if a different value / ethic was to replace yield maximisation as the basis of soil tests, then, 'in theory', all of the empirical field trial work used to create the current yield curves would have to be redone using the new value system's measurements, which would be a gargantuan task. However, it appears that in a lot of cases (making a broad sweeping generalisation), when soil nutrient levels are optimum for yield (i.e. maximise plant growth / performance), they are not to far wrong for optimising levels for other value systems. One clear exception to this is nitrogen, which in large amounts, can increase pests and/or diseases. So, even though the value system of current soil tests has been designed for yield maximisation, in many, but not all, cases is still a pretty reasonable guide

[3] https://en.wikipedia.org/wiki/Scientism

for different objectives, because if available nutrient levels are too far from what is required for yield maximisation, then, other crop production objectives (flavour, nutrient content, etc.) are also unlikely to be achieved.

4. Understanding yield curves

First, despite everything discussed above, the really impressive thing about soil tests, is just how **accurate**[1] they actually are, and it is testament to the hard work of soil chemists and agronomists over many decades that they are as good as they are. However, the key message, is that while they are accurate, they are often nowhere near as **precise**[1] as would be ideal when it comes to using the test results to predict what yield will actually eventuate in the field and how much fertiliser is required. Science never achieves complete precision: even quantum physicists working at 16 decimal points, have error terms on their measurements. Soil tests, therefore, really should have the margin of error (the limit of precision) of both the laboratory test and especially the yield curve clearly stated.

4.1. What a 'real' yield curve looks like

To put this graphically Figure 6 shows the yield curve from Figure 2, but with a thick, fuzzy edged line to indicate the margin of error.

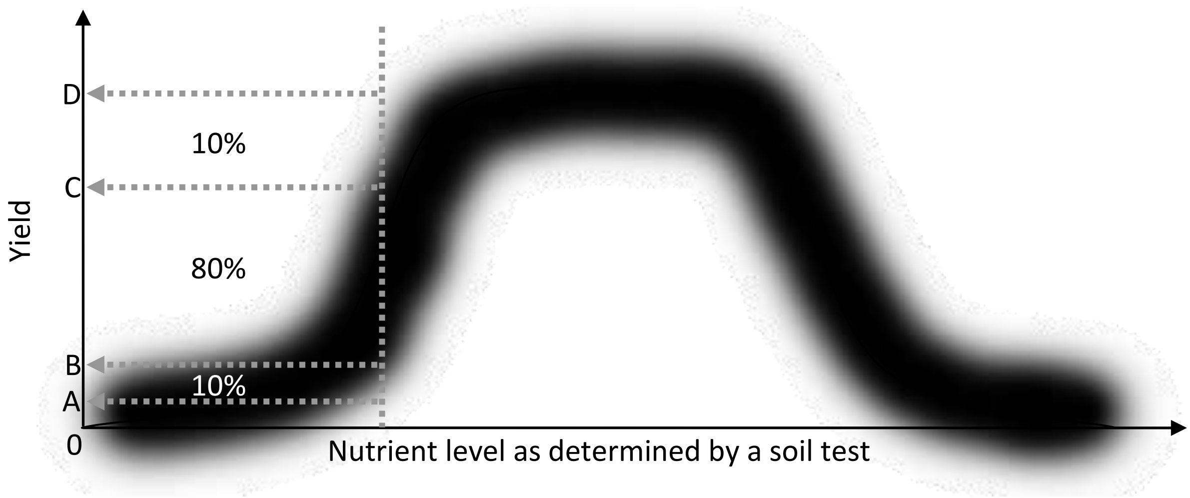

Figure 6. A yield curve using a wide, fuzzy edges line, to indicate the precision (margin of error) of the test and the resulting wide range of possible yields for a given nutrient level / test result.

The darker central part of the line covers the 80% confidence interval, i.e. there is a 80% chance of the 'true' crop yield (i.e. the actual yield of the crop in question in the field the soil test came from) lying within this area. The fuzzy grey edges are the remaining 20%, 10% on either side, i.e., there is a 20% chance of the true yield lying within this area, even though it has almost the same area as the dark central band. So for any given nutrient level, the real yield will lie somewhere within the band, but exactly where, it is impossible to tell.

4.2. The imprecision of yield curves

What this means for the real world of farming is that for any given nutrient level, the predicted crop yield can vary widely, especially if the nutrient level is on the exponential part of the bell curve. For example, in Figure 6, the vertical grey dashed line represents a soil test result / soil nutrient level. However, the actual yield predicted by this precise figure is represented by the four horizontal dashed grey lines, and varies from A at the bottom, with very poor growth, to D at the top with is nearly at maximal growth. This is clearly a very big margin of error! To expand, there is a 20% chance that the actual yield will lie somewhere between A & B and C & D, and an 80% chance it will lie between B & C. Even the 80% probability zone is still very large with yields varying from very poor to quite acceptable.

In comparison, Figure 7 has a test result / soil nutrient level in the middle of the bell curve. As the curve is flat at this point, the range of possible yields is much smaller, and nearly all of them are in the top 25% of possible yields for the crop.

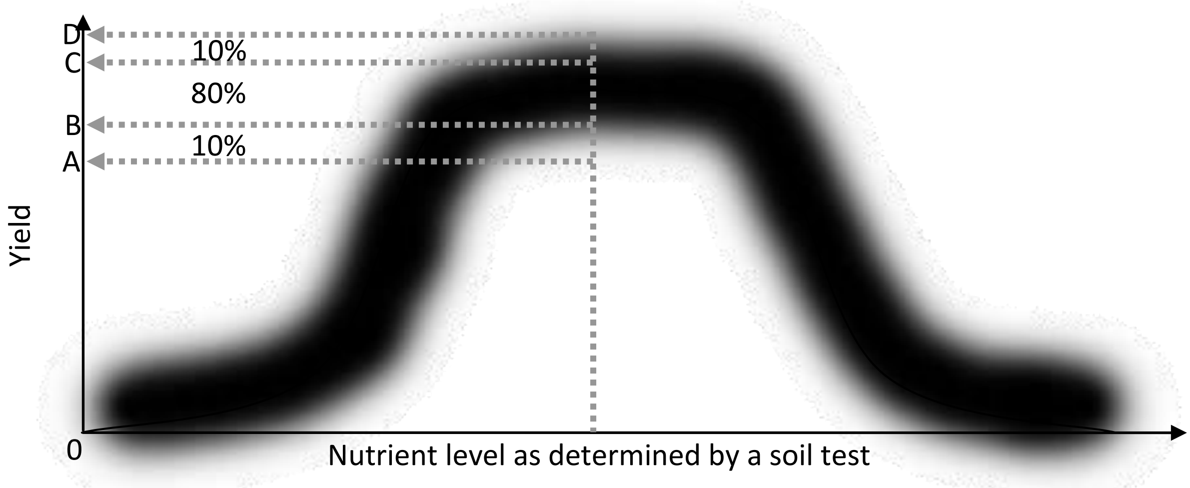

Figure 7. A fuzzy yield curve with a soil test result / soil nutrient level in the middle of the curve, illustrating the much smaller resulting range of possible plant yields compared to Figure 6.

NB. The actual margin of error of most yield curves are considerably smaller than the above hypothetical examples, which have been deliberately large for illustrative purposes.

It is also worth noting the difference in the precision of the two components of this process: 1) the laboratory test and 2) the yield curve. Chemical based laboratory tests are generally both accurate and precise, i.e., if you have a sample of soil, randomly divide it up into lots of sub-samples, and do a soil test on each of the samples, the results will be all very similar. It is therefore, mainly the yield curves where the lack of precision comes from, as these have been created by lots of empirical field trials with all the associated issues as discussed in section 3.4.

To summarise, for any one given crop, your mileage / yield will vary, possibly a lot, as extrapolating from the laboratory soil test result to the actual yield and fertiliser requirements can have a large margin of error.

4.3. Soil tests as a guide not an oracle

This is why experienced farmers and growers often remark that they take soil tests with a pinch of salt, as they know that the actual yields they get, and response of the crop to any fertiliser recommendations based on soil test results, can be both variable, and/or imprecise for their farm. The imprecision can be both an over and underestimation of yield / fertiliser response, e.g., sometimes there is no crop response to applied fertiliser when the tests indicated there should and conversely there is a response to applied fertilisers even when the test indicated applying fertiliser wont have any effect. Fundamentally, there is nothing wrong with the tests and nothing wrong with the farmers judgement. What is not mentioned is the margin of error, which is why, scientifically, both test and farmer can be right at the same time.

And that is why the critical thing with soil tests is not to take any one result as the truth, the whole truth and nothing but the truth. Rather, soil test should be conducted on a regular basis, i.e. every few years, to produce a long term trends in soil nutrient levels, which will show if they are increasing or decreasing over time, and if there are any outlier results (e.g., due to sampling variation, see section 11) these will stand out and can be discounted.

Fertiliser recommendations then need to be moderated through accumulated experience of how crops and pasture respond on any given farm even field, i.e., if the recommended fertiliser rates consistently fail to produce a crop response, then the level of soil nutrients at which fertilisers should applied at can be reduced, or, if putting on more fertiliser than the recommended rate consistently results in an increase in yield, then the soil nutrient level at which fertilisers should be applied at should be increased.

In the final conclusion, soil nutrient management is therefore both a science and an art. Chemical soil tests are by far the most accurate means there are of determining soil nutrient levels and therefore crop performance / yield, however, due to the imprecision of the overall system, especially yield curves, farmers and growers need to combine the results with their experience of the performance of their crops and pasture on their soils to decide how much, if any, fertiliser to apply.

5. The details of soil nutrient management

The previous three sections have explained the fundamentals of soil nutrient tests and their limits. However, there are a number of additional more specific issues that are also important components of a general understanding of soil nutrients, soil testing and fertiliser recommendations.

5.1. The yield curve thicket

The nice bell-shaped yield curve used in the previous sections is a simplification of real world yield curves, created to help explain the concept. Real yield curves varies considerably among the nutrients, for example, micro-nutrients, such as the metal boron, typically have a pronounced peak (Figure 2), i.e. there is only a small range of the nutrient that allows plants to thrive, to little and too much are deleterious. For example, excess levels are often toxic with excess boron having a herbicidal effect: whole apple orchards have been killed by too high a rate of foliar boron spray!

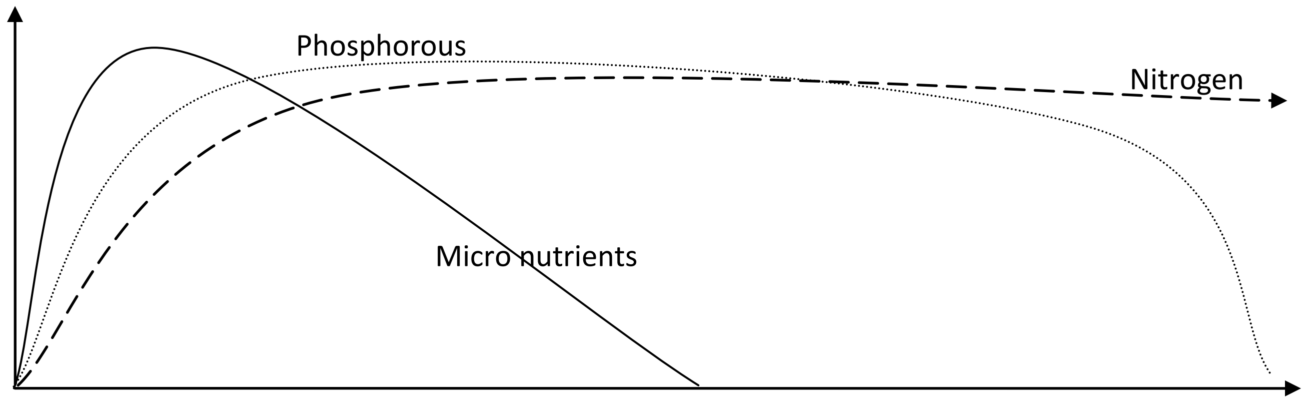

Figure 8. Different yield curves of micro nutrients, phosphorus and nitrogen.

In comparison, the macro nutrients, such as nitrogen and phosphorus, have flatter and much longer curves (Figure 2), as plants will successfully grow, and also show a growth response to fertiliser, over a much wider range of nutrient levels. It is therefore also harder to kill plants with macro-nutrients than micro nutrients as much higher levels of nutrient application are required to have an effect. However, this is still possible, as demonstrated by the pasture killed by fish fertiliser in Figure 3.

What this means is that while much smaller quantities of the micro-nutrients are required for healthy plant growth than the macro-nutrients, micro does not mean less important, conversely, as the optimal range of levels of micro-nutrients is much smaller than macro nutrients, while having a little bit too much or too little NPK is unlikely to have a large effect on yields, having an excess or shortage of micro-nutrients can have large impacts on plant health. Therefore, more focus, rather than less, should be given to micro- than macro-nutrient levels.

Building on this is the utterly critical interaction between soil pH and nutrient, especially micro-nutrient levels. However, to fully understand this issue an understanding of how plants absorb nutrients is required.

5.2. Plants are fussy 'eaters'

As touched on in section 3.1, plants can only absorb the nutrients they need to grow and be healthy in a small range of forms. So while soils can contain very large amounts of any given nutrient, for example there may be two tonnes of total phosphorous per ha, the amount of P that is in a chemical form that plants can absorb is often much lower, a few hundred grams per hectare in the case of P, much of the rest is part of the rock that makes up silt and sand particles and stones. The chemical forms of the elements that plants can take up are listed in Table 2.

Table 2. Forms of essential elements taken up by plants.

Element	Abbreviation	Form absorbed
Nitrogen	N	NH_4^+ (ammonium) and NO_3^- (nitrate)
Phosphorus	P	$H_2PO_4^-$ and HPO_4^{-2} (orthophosphate)
Potassium	K	K^+
Sulphur	S	SO_4^{-2}(sulfate)
Calcium	Ca	Ca^{+2}
Magnesium	Mg	Mg^{+2}
Iron	Fe	Fe^{+2} (ferrous) and Fe^{+3} (ferric)
Zinc	Zn	Zn^{+2}
Manganese	Mn	Mn^{+2}
Molybdenum	Mo	MoO_4^{-2} (molybdate)
Copper	Cu	Cu^{+2}
Boron	B	H_3BO_3 (boric acid) and $H_2BO_3^-$ (borate)

5.2.1. Inorganic vs. organic chemical uptake

The key point of this list is that it is very short! Next is that plants take up nutrients in mineral / inorganic (as in inorganic chemistry) rather than biological / organic (as in organic chemistry) forms[4]. This was Justus von Liebig's big discovery, as before Liebig, it was believed plants absorbed their requirements in organic forms - based on simple observations that putting manure on plants made them grow better. This is why Liebig is referred to as the 'father of agricultural chemistry'[5]. In turn, it was Liebig's discovery that 'created' mineral fertilisers and hence the creation of the fertiliser industry.

Returning to Table 2 There is a wee bit of latitude in the chemicals listed, as plants are sometimes able to take up small amounts in other forms, and recently it has been shown that plants can take up small amounts in biological forms, contrary to Liebig's discovery. However, the amounts are generally so small to be of little or no consequence in terms of general plant performance in agriculture, and the nutrient forms in Table 2 dominate.

[4] Organic chemistry is the main sub-division of the science of chemistry, it exclusively deals with chemistry involving compounds that have carbon-hydrogen bonds, i.e., the hydrocarbons, i.e., it is the chemistry of life. Inorganic chemistry is all other chemistry, i.e., all chemistry except the chemistry of life.
[5] https://en.wikipedia.org/wiki/Justus_von_Liebig

5.3. Competition among the elements

This restrictive list is the reason why soils can be brimming with large total amounts of any given element, but why most of that element is completely untouchable by plants. And, looking at it from the opposite perspective, the reason the list is so restrictive, is because there are only a few mechanisms that plants have evolved to get nutrients across, what is otherwise, an impermeable barrier round their roots. This is why only simple / inorganic nutrients are taken up, as only small molecules are able to be transferred across the root surface barrier.

In most cases the take-up of nutrients is also an active process mediated by some rather impressive biochemistry, the details of which are not critical here. However, there is one outcome that this chemistry has that does have a big impact on how we farm, and it is down to evolution being rather economical, in that it would rather make-do, rather than do things 'properly'. This means some nutrients share the same uptake mechanism, rather than having one mechanism per nutrient. This, in turn, means the plant cannot alter the proportions of nutrients it takes up that share the same uptake pathway. This then, means that the nutrients get taken up in the proportion that exists in the soil. Therefore if a plant is deficient one of those nutrients it cannot take extra amounts of that nutrient up, and perhaps worse, if one of the nutrients is in excess in the soil and even if the rest are present in optimal amounts, the excess nutrient will get taken-up in larger amounts (due to its larger proportion in the soil) which can cause the plant to be deficient in the other nutrients that share the same uptake pathway.

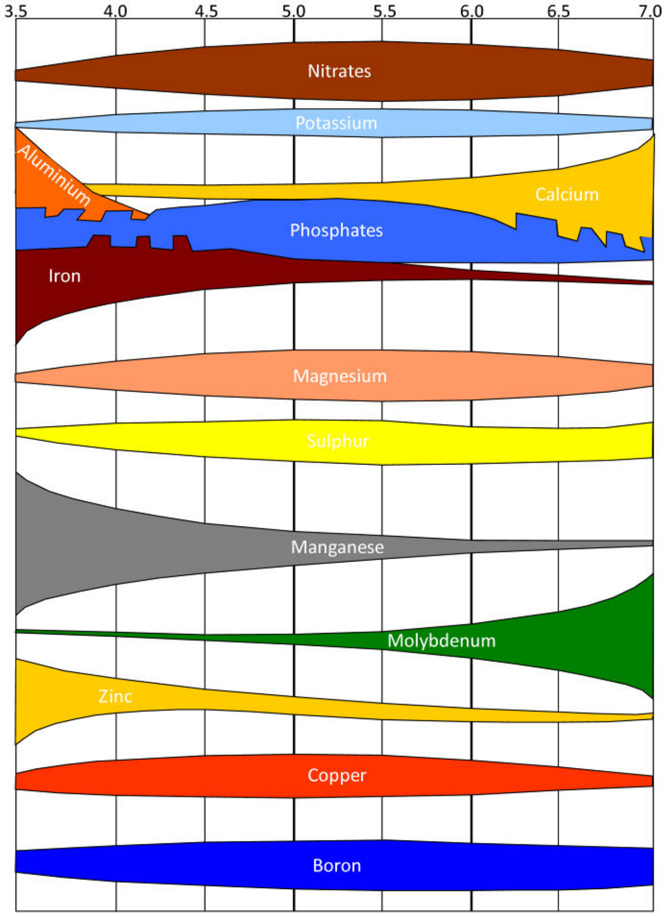

Figure 9. Effect of pH on nutrient availability, the wider the bar, the greater the nutrient availability. The greatest level of plant nutrients are available between pH 5.5 to 6.5. Where nutrients have the same biochemical uptake pathway, their availability curves overlap, with the castellated areas indicating where uptake of one nutrient will reduce uptake of the other.

This can be thought of as having a bucket, representing the soil, filled with marbles of two colours, red for the nutrient present in large amounts and blue for the scarce nutrient, i.e. there are lots of red marbles and only a few blue marbles. Using a soup ladle, to represent the plant roots uptake mechanism, it is impossible to only take up blue marbles, every ladle will contain mostly red marbles, with only a few blues in the same overall average proportion of the red and blue marbles in the bucket.

In short, excessive amounts of some nutrients will cause plants to be deficient in others. This can be further exacerbated by soil chemistry and biology with excess levels of some nutrients causing chemical transformations of others leading to unavailability. This can have some particularly serious impacts on livestock, such as nutrient deficiency sickness being caused by an excess of another nutrient, which in turn is the result of an excess of that nutrient in pasture which is ultimately caused by an imbalance in soil nutrients.

The elements for which this occurs are shown in Figure 9 with the uptake curves overlapping and castellated. These are principally calcium, phosphates, aluminium and iron, but there are others, especially among the micro-nutrients.

5.4. We need to talk about pH

However, the more important message from Figure 9 is the effect of pH i.e. the acidity or alkalinity of the soil and the figure speaks much more clearly than words: where pH is to low or to high, nutrient availability either heads to zero or heads to infinity (or at least very large values). Again leaving aside some very complex chemistry, that has kept legions of soil scientists employed for life, the key message is that if pH is too far from the optimum of around 5.5 to 6.5, then nutrient uptake is going to be sub-optimal. And while it is well known that some crops like their soil more acid, and others more alkaline, and beyond crops, there are species that can only grow at the extremes of the pH spectrum, the overall point is still 100% correct - if your pH is too far from optimum, then even the best nutrient management system, cannot achieve healthy crops and pasture.

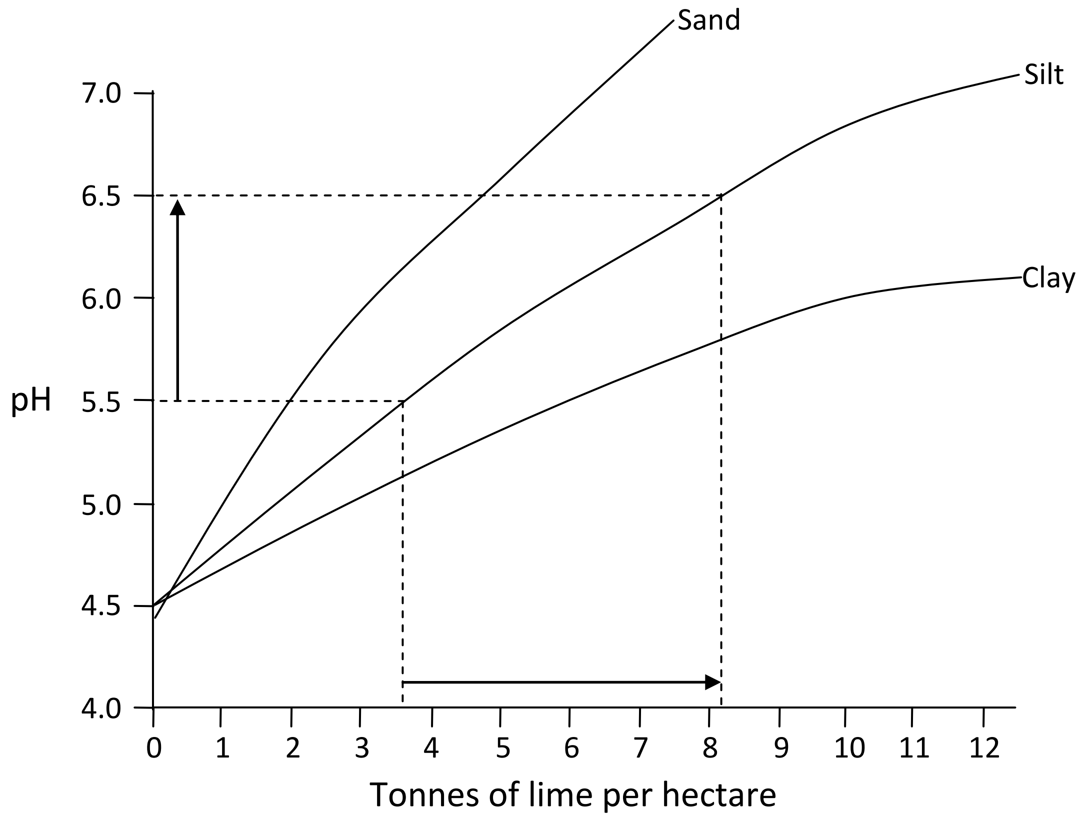

Figure 10. The amount of lime with a neutralising value of 100 required to raise the pH on sand, silt and clay soils. For example, to increase the pH of a silt soil from 5.5 to 6.5 (horizontal dotted lines) requires 4.5 (8.2 - 3.7 = 4.5) tonnes of lime per hectare (vertical dotted lines).

So of all the things tested in a soil test, the first and most important to get right, is pH. Fortunately getting it right is straightforward, applying lime, in amounts that are well prescribed according to your soil type (sand, silt, clay, peat) and the starting pH, followed by ongoing testing to ensure optimum pH is reached. This information is typically included in soil test results and if not, a local soil scientist or adviser can easily work out your requirements. They can also provide the data that they used to calculate the amounts for your particular soil and the neutralising value of the lime you are using so you can work this out for yourself in future. An example of general liming curve is given in Figure 10.

6. Conclusions

All living things are made from the chemical elements, in a pretty narrow range of proportions, so whether they be plants or animals, if they are deficient in one or more of the elements / nutrients they wont thrive, or worse they will be come sick, and even die. As plants are the foundation of the food chain, it is therefore imperative that they have access to the right amounts of nutrients so both they, and the species that eat them, including people, are also healthy. Apart from carbon and oxygen, plants get all the rest of the nutrients they need via the soil, so for healthy plants, it is essential to have the right amounts of nutrients, in the right chemical forms, in the soil. By far the most accurate way to determine the amounts of plant nutrients in the soil are 'chemical' soil tests. However, a lot of mythology and misunderstanding has built up around soil tests, especially in terms of their precision, which means there is considerably more latitude in fertiliser recommendations than the hard and fast numbers on soil tests indicate. Despite the lower level of precision than commonly thought, and despite the significant technical difficulties in developing soil tests, the exceptionally impressive thing about them is just how good they are. Therefore, there are no alternatives to chemical soil testing for accurately managing soil nutrient levels, and therefore soil health, crop and livestock health and ultimately human health. If soil is the foundation of good farming, the foundation of good soil management, is soil testing.

7. Acknowledgments

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