Soil Conditions and Plant Growth

Edited by Peter J. Gregory and Stephen Nortcliff

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Contents

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Preface

Since the last edition of *Russell's Soil Conditions and Plant Growth* in 1988, soil, plant and crop sciences have moved on considerably. For a long time during these 24 years, there was a diminishing interest in soil science as an underpinning element of crop production largely because the higher income countries of the world were food secure and, indeed, at times awash with surplus crops. Soil science became an environmental science with a much broader remit, and courses at universities changed to meet the training of this new wave of students. One consequence of these changes was that the traditional publisher of this-textbook saw no demand for a new edition.

Recently, though, the mood has changed again, and both the rising awareness of global food insecurity and the need for soils and land to deliver simultaneously food and fibre and other ecosystem goods and services have focused attention on the requirement to better understand and manage the many interactions that occur between soils and plants. What better time for a new edition of *Soil Conditions and Plant Growth* to examine these interactions?

In preparing for this book, we decided at an early stage to let go of some of the content of the previous editions. There are now many introductory textbooks on soils and soil science; hence, we have quite deliberately excluded from this edition elements of pedology, chemistry, microbiology and soil survey that featured previously. Instead, we have tried to focus on what has always been the core feature of this book – the interactions between soils and plants. We have included accounts that detail how plants respond to soil properties but also how plants themselves are key agents in soil formation and modifiers of their environment.

We have also chosen writers with some experience of how soils can be managed in both agricultural and ecological contexts to promote crop production but also to deliver high-quality water supplies, cope with the warming climate and all of the many other necessities of life that we have come to expect from our soils.

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Finally, we would like to thank acknowledge with gratitude the encouragement that we received in our careers from Professors Walter Russel, Dennis Greenland and Alan Wild and to Wiley-Blackwell for taking on the publication of this book. We also thank our many authors for so readily agreeing to write for us and for their enthusiasm in updating what, for many of us as students, was a soil science classic. This year, 2012, is the centenary of the first edition of Russell's book, and we hope that our readers will find the same inspiration as previous generations of students and researchers.

Peter J. Gregory
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March 2012

1 The historical development of studies on soil–plant interactions

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1.1 Introduction

How plants grow and how this growth varies through time and in response to changing conditions has been an interest of people for millennia. From the early cultivators to present-day gardeners, there has been a fascination in how a flourishing plant can be derived from a dry, apparently lifeless seed. Furthermore, there has been recognition that plant growth shows different patterns in response to weather conditions and that it varies from place to place. As global population continues to increase the need to understand the growth of plants and the role of soils in crop production becomes increasingly important. The demand for both food and biomass-derived energy from plants is increasing, so we must also seek to understand how to allocate land for multiple purposes. Soils must be used for these services and to obtain other essential services such as clean water and a diverse soil community of organisms.

Many early civilisations appear to have compiled information on plant growth and crop husbandry, and there was an extensive literature on agriculture developed during Roman times, which provided important guidance on crop growth and management for many centuries after the fall of the Roman Empire. The Roman literature was collected and condensed into one volume about the year 1309 by a senator of Bologna, Petrus de Crescentius (the book was made more widely available when published in 1471), whose book was one of the most popular treatises on agriculture of any time, being frequently copied, and in the early days of printing, passing through many editions. Many other agricultural books appeared in the fifteenth and early sixteenth centuries, notably in Italy and later in France. In some of these are found certain ingenious speculations that have been justified by later work. Such, for instance, is Palissy’s remarkable statement in 1563:

> You will admit that when you bring dung into the field it is to return to the soil something that has been taken away…. When a plant is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers…. Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away.

But while some of these speculations have been confirmed, many in other sources have not, and the beginnings of agricultural chemistry was to take place later when we had learnt the necessity for investigating possible relationships and pathways using experiments.

1.2 The search for the ‘principle’ of vegetation, 1630–1750

It was probably discovered at an early stage in agricultural development that manures, composts, dead animal bodies and parts of animals, such as blood, all increased the-productivity of the land; and this was the basis of the ancient saying that ‘corruption is the mother of vegetation’. Although there was empirical evidence for this linkage, the early investigators consistently ignored this ancient wisdom when they sought for the ‘principle’ of vegetation to account for the phenomena of soil fertility and plant growth. Thus, the great Francis Bacon, Lord Verulam, believed that water formed the ‘principal nourishment’ of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, though he also considered that each plant drew a ‘particular juyce’ from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Similarly, van Helmont (1577–1644) regarded water as the sole nutrient for plants, and his interpretation of a carefully undertaken experiment in which he grew willows concluded that water was the principal requirement for plant growth (van Helmont, 1648).

Robert Boyle (1661) repeated the experiment with ‘squash, a kind of Italian pompion’ and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, ‘salt, spirit, earth, and even oil, may be produced out of water’. While these experiments were laudable, they ignored the part played by air, and in the van Helmont experiment there was a small reduction in the amount of soil present, which was ignored, although we now know this to be significant. In some respects, this might be taken as a guide for many of the future experiments undertaken in agriculture; if the hypotheses are wrong and other hypotheses are ignored, conclusions which may appear to be valid will often turn out to be incorrect because the alternatives have been ignored.

The primacy of water in plant growth was questioned by an experiment published by John Woodward in a fascinating paper (1699). Based on the experiments of van Helmont and of Boyle, he grew spearmint in water obtained from various sources and noted that all of these plants were supplied with an abundance of water so that all should have made equal growth had nothing more been needed. The amount of growth, however, increased with the impurity of the water (Table 1.1). He concluded:

> Vegetables are not formed of water, but of a certain peculiar terrestrial matter. It has been shown that there is a considerable quantity of this matter contained in rain, spring and river water, that the greatest part of the fluid mass that ascends up into plants does not settle there but passes through their pores and exhales up into the atmosphere: that a great part of the terrestrial matter, mixed with the water, passes up into the plant along with it, and that the plant is more or less augmented in proportion as the water contains a greater or less quantity of that matter; from all of which we may reasonably infer, that earth, and not water, is the matter that constitutes vegetables.

Taking account of the results in his experiment, he discussed the use of manures and the fertility of the soil from this point of view, attributing the well-known falling off in crop yield when plants are grown for successive years on unmanured land to the circumstance that:

Table 1.1 Growth of spearmint using water from different sources.

Source: From Woodward (1699).

Source of water	Mass (g) of plants when planted	Mass (g) of plants when harvested	Mass (g) gained in 7 days	Expense (g) of water (transpiration)	Ratio increase in mass:mass water used
Rain water	1.83	2.96	1.13	220.3	1:195
River Thames	1.81	3.50	1.69	161.5	1:95.6
Hyde Park Conduit	7.13	16.14	9.01	851.5	1:94.5
Hyde Park Conduit plus 105 g garden mould	5.96	24.36	18.40	968.8	1:52.7

> the vegetable matter that it at first abounded in being extracted from it by those successive crops, is most of it borne off…. The land may be brought to produce another series of the same vegetables, but not until it is supplied with a new fund of matter, of like sort with that it at first contained; which supply is made several ways, either by the ground's being fallow some time, until the rain has poured down a fresh stock upon it; or by the tiller's care in manuring it.

The best manures, he continued, are parts either of vegetables or of animals, which ultimately are derived from vegetables.

For a time there was little progress in relation to what plants needed in addition to water and how these needs might be met. Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse-hoe by Jethro Tull, an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil into a fine, crumbly state for plant growth. Tull (1731) was more than an inventor; he discussed in most picturesque language the sources of fertility in the soil. In his view, it was not the juices of the earth but the very minute particles of soil loosened by the action of moisture that constituted the ‘proper pabulum’ of plants. The pressure caused by the swelling of the growing roots forced these particles into the ‘lacteal mouths’ of the roots, where they entered the circulatory system. All plants lived on these particles, i.e. on the same kind of food; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the ‘pasture of the plant’ and also enabled the soil to better absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

The position at the end of this period cannot better be summed up than in Tull’s own words: ‘It is agreed that all the following materials contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food: (1) nitre, (2) water, (3) air, (4) fire, (5) earth’.

1.3 The search for plant nutrients

1.3.1 The phlogistic period, 1750–1800

Great interest was taken in agriculture in the UK during the latter half of the eighteenth century. Many experiments were conducted, facts were accumulated, books written and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home 'to try how far chymistry will go in settling the principles of agriculture' (1757). The whole art of agriculture, he says, centres in one point: the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its fertility on exposure to air, which therefore supplies another food. Home established pot experiments to ascertain the effect of various substances on plant growth. 'The more they [i.e. farmers] know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road.' Saltpetre, Epsom salts, vitriolated tartar (i.e. potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil and fire in a fixed state. As further proof he shows that 'all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire'.

Between 1770 and 1800, work was done on the effect of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of nature, but its agricultural significance was not recognised until later. Joseph Priestley, knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc., and realising that some natural purification must go on, or life would no longer be possible, was led to try the effect of sprigs of living mint on vitiated air (1775). He found that the mint made the air purer and concludes ‘that plants, instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it’. But he had not yet discovered oxygen and so could not give precision to his discovery; and when, later on, he did discover oxygen and learn how to estimate it, he unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity for light. He was therefore unable to answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Jan Ingen-Housz (1779) who reconciled both views and showed that purification goes on in light only, while vitiation takes place in the darkness. Ingen-Housz’s conclusions might be summarised as follows: (1) light is necessary for this restoration (this we would now know as photosynthesis); (2) only the green parts of the plant actually perform restoration and (3) all living parts of the plant ‘damage’ the air (respire), but the extent of air restoration by a green plant far exceeds its damaging effect. Jean Senebier (1782) working in Geneva also concluded that the plant–atmosphere interactions were significant.

1.3.2 The period 1800–1860

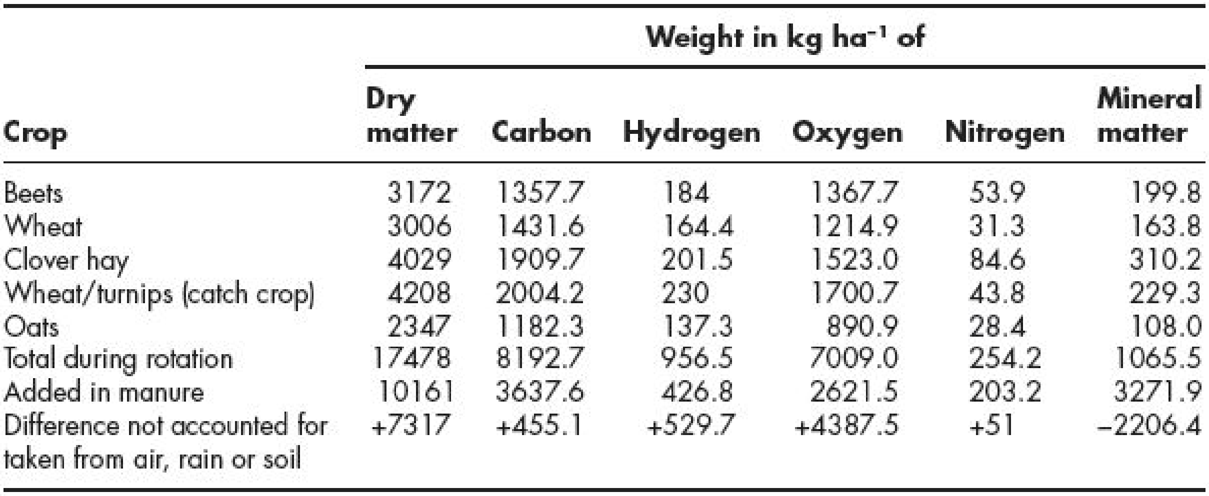
The foundation of plant physiology

Progress to this point had been constrained by methodologies which were known and accepted. To gain new insights and further investigate some of the speculation, particularly in relation to the plant–atmosphere links, new methods were required. The work of Nicholas Theodore de Saussure (1804) in the early nineteenth century in establishing the broad principles of the quantitative experimental method, in some respects produced the paradigm shift which proved the basis for modern agricultural chemistry. The work of Boussingault, Liebig, Lawes and Gilbert drew on this new experimental method which still provides the basis of many investigations. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by ‘carbonisation’. He was thus able to demonstrate the central fact of plant respiration – the absorption of oxygen and the evolution of carbon dioxide – and further show the decomposition of carbon dioxide and evolution of oxygen in light. Carbon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots, he concluded that even under the most favourable conditions the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen which he described as an essential part of vegetation and, as he had shown, was not assimilated directly from the air, and also ash constituents, which he noted contributed to the solid parts of plants, just as with animals. Further, he showed that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, were absorbed to different extents. Passing next to the composition of the plant ash, he showed that it was not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a plant is grown from seed in water, there is no gain in ash: the amount found at the end of the plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus, he disposed finally of the idea that the plant *generated* potash.

While in retrospect we see the considerable insight into the basis of plant growth and plant nutrition presented by de Saussure, the ideas and approaches did not gain general acceptance. The two great books on agricultural chemistry then current still belonged to the old period. A. von Thaer and Humphry Davy did not realise the fundamental change in perspective introduced by de Saussure. Thaer published his *Grundsätze der rationellen Landwirtschaft* in 1809–1812, which was translated into English as late as 1844 by Cuthbert Johnson. In it he adopted the prevailing view that plants draw their carbon and other nutrients from the soil humus. Humphry Davy's book (1813) grew out of the lectures on agricultural chemistry which he gave annually at the Royal Institution between 1802 and 1812; it forms the last textbook of the older period. While no great advance was made by Davy himself, he carefully sifted the facts and hypotheses of previous writers and gives an account, which, although defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. His great name gave the subject an importance it probably would not otherwise have had. He did not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of the air: some plants, he says, appear to be supplied with carbon chiefly from this source, but in general he supposes the carbon to be taken in through the roots. Davy presented a list of sources of this carbon, but there was little supporting experimental evidence and subsequently the sources have been shown to be false, although Davy's reputation meant they persisted. His insistence on the importance of the physical properties of soils – their relationship to heat and to water – was more accurate and marks the beginning of soil physics. In mainland Europe, to an even greater extent than in Britain, it was held that plants drew their carbon and other nutrients from the soil humus.

Table 1.2 Budgets of dry matter, carbon, hydrogen, oxygen nitrogen and mineral matter at Pechelbronn, Alsace.

Source: From Boussingault (1841).



	Weight in kg ha⁻¹ of					
Crop	Dry matter	Carbon	Hydrogen	Oxygen	Nitrogen	Mineral matter
Beets	3172	1357.7	184	1367.7	53.9	199.8
Wheat	3006	1431.6	164.4	1214.9	31.3	163.8
Clover hay	4029	1909.7	201.5	1523.0	84.6	310.2
Wheat/turnips (catch crop)	4208	2004.2	230	1700.7	43.8	229.3
Oats	2347	1182.3	137.3	890.9	28.4	108.0
Total during rotation	17478	8192.7	956.5	7009.0	254.2	1065.5
Added in manure	10161	3637.6	426.8	2621.5	203.2	3271.9
Difference not accounted for taken from air, rain or soil	+7317	+455.1	+529.7	+4387.5	+51	−2206.4

The foundation of agricultural science

To this point, experiments had been conducted either in the laboratory or in small pots: around 1834, however, J. B. Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Pechelbronn in Alsace. These were the first of their kind: to Boussingault, therefore, belongs the honour of having introduced the method by which the new agricultural science was to be developed. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crop obtained, and at the end of the rotation drew up a balance sheet, showing how far the manures had satisfied the needs of the crop and how far other sources of supply – air, rain and soil – had been drawn upon. The results of one experiment are given in Table 1.2. At the end of the period, the soil had returned to its original state of productiveness, hence the dry matter, carbon, hydrogen and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure.

The rotation had not impoverished the soil so he concluded that nitrogen may be taken directly in to the plant if the green parts are capable of fixing it. Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth, with soils and with problems in animal nutrition. Unfortunately, the classic farm of Pechelbronn did not remain a centre for agricultural research, and the experiments came to an end in 1870.

During this period (1830–1840), Carl Sprengel was studying the ash constituents of plants, which he considered were probably essential to nutrition (1832). Schübler was working at soil physics, and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

But all this was changed in 1840 when Liebig's famous report to the British Association upon the state of organic chemistry, published as *Chemistry in Its Application to Agriculture and Physiology* in 1840 (Liebig, 1840), gave rise to the need to rethink the world of science. Liebig was highly critical of the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. 'All explanations of