Soil Conditions and Plant Growth

Edited by Peter J. Gregory and Stephen Nortcliff

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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.

The contributors to this book would particularly like to thank (1) Dr Clare Benskin (Lancaster University, UK), Dr Tim George (James Hutton Institute, UK), Dr Alan Richardson (CSIRO, Australia) and Dr Ben Turner (Smithsonian Tropical Research Institute, Republic of Panama), who all contributed helpful material or input to preparing Chapter 5; (2) the financial support of The Scottish Government Rural and Environment Research and Analysis Directorate for Chapter 6, which is dedicated to the memory of Dr Duncan J. Greenwood (1932–2010); and (3) Dr Jos Raaijmakers and Dr Paolina Garbeva for providing the bacterial strain referred to in Figure 11.10.

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
Stephen Nortcliff
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

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> 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

Table 1.1 Growth of spearmint using water from different sources.

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

Source: From Woodward (1699).

> 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:

> 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,

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

	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

Source: From Boussingault (1841).

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.

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 chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids and bases are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations.' Liebig stated that the experiments quoted by the physiologists in support of their view are all 'valueless for the decision of any question'. Liebig's ridicule did what neither de Saussure's nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source other than carbon dioxide, and for a time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water and nitrogen from ammonia. Certain mineral substances were essential: alkalis were needed for neutralisation of the acids made by plants in the course of their vital processes, phosphates for seed formation and potassium silicates for the development of grasses and cereals. The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if carbonic acid is being generated in the soil, for it enters the plant roots and affords extra nutrient over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

Liebig further argued that the alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant roots, and the dissolved material now enters the plant.

Nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile, it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made, it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made up on these lines and placed on the market.

Liebig's book (1840) was meant to attract attention to the subject, and it did; it rapidly went through several editions, and as time went on Liebig developed his thesis and gave it a quantitative form: 'The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure.' He further adds what afterwards became known as the Law of the Minimum, 'by the deficiency or absence of one necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which that one constituent is indispensable'. These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. 'If the soil be suitable, if it contain a sufficient quantity of alkalis, phosphates, and sulphates, nothing will be wanting. The plants will derive their ammonia from the atmosphere as they do carbonic acid', he writes in the *Farmer's Magazine*. Ash analysis led him to consider the turnip as one of the plants 'which contain the least amount of phosphates and therefore require the smallest quantity for their development'. These and other practical deductions were seized upon and shown to be erroneous by Lawes and Gilbert, who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate was, in Philip Pusey's words: 'The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr Lawes.'

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but the compounds were rendered insoluble by fusion with lime and calcium phosphate so that the manure should not too readily wash out in the drainage water. Not until Way (1850) had shown that *soil precipitates soluble salts of ammonium, potassium and phosphates* was the futility of the fusion process discovered, did Liebig (1851) recognise the error he had made.

1.3.3 The second half of the nineteenth century

Meanwhile the great field experiments at Rothamsted had been started by Lawes and Gilbert in 1843. These experiments were conducted on the same general lines as those begun earlier by Boussingault, but they have the advantage that they still continue, having been on the same ground without alteration, except in occasional details, since 1852. The mass of information now accumulated is considerable and has become an invaluable source of data as we seek to understand aspects of sustainability and possible responses to environmental change (see, e.g. Leigh and Johnston, 1994). The experiments rapidly provided information and, by as early as 1855, the following points were clear:

1. Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, for

example turnips require large amounts of phosphates, although only little is present in their ash.

2. Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost equally good. Without an adequate supply, no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behave abnormally.
3. Soil fertility may be maintained for some years at least by means of artificial manures.
4. The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier published a somewhat similar but less definite view of nutrition: Liebig had brought matters to a head and made people look at their cherished, but rarely examined, convictions. The effect of the stimulus he gave can hardly be over-estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential for all plants, is advantageous for the nutrition of many cereals.

In two respects, however, the controversies continued for many years. Farmers were slow to believe that 'chemical manures' could ever do more than stimulate the crop and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this assertion; manured year after year with the same substances and sown always with the same crops, they even now, after more than a 150 years of chemical manuring, continue to produce good crops, although secondary effects have sometimes set in. In France, the great missionary for artificial manures was Georges Ville, whose lectures were given at the experimental farm at Vincennes during 1867 and 1874–1875. He went even further than Lawes and Gilbert and maintained that artificial manures were not only more remunerative than dung but were the only way of keeping up fertility (Ville, 1879). In recommending mixtures of salts for manure, he was not guided by ash analysis but by field trials. For each crop, one of the four constituents, nitrogen compounds, phosphates, lime and potassium compounds (he did not consider it necessary to add any others to his manures), was found by trial to be more required than the others and was therefore called the 'dominant' constituent. For wheat he concluded that on his soil it required a good supply of nitrogen, less phosphate and still less potassium (Table 1.3).

Other experiments of the same kind showed that nitrogen was dominant for all cereals and beetroot, potassium for potatoes and vines, and phosphate for turnips and swedes. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was at that time not good enough for this purpose. Instead, he drew up a simple scheme of plot trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small vessel absorbed during the course of the

Table 1.3 Yield data for wheat grown at Versailles, France.

Constituent added	Yield t ha^{-1}
Normal manure	2.98
Manure without lime	2.84
Manure without potash	2.14
Manure without phosphate	1.83
Manure without nitrogen	0.97
Soil without manure	0.83

Source: From Ville (1879).

month seven-eighths of the air present. De Saussure, however, denied that plants assimilated gaseous nitrogen. J. B. Boussingault's pot experiments showed that peas and clover could get nitrogen from the air while wheat could not, and his rotation experiments emphasised this distinction. While he did not make as much of this discovery as he might have done, he later fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes et al. (1861) in the most rigid demonstration that had yet been attempted. A full summary of this work is provided in Lawes and Gilbert (1889). Plants of several natural orders, including the Leguminosae, were grown in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all traces of nitrogen compounds, while the plants were kept throughout the experiment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food, the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops, this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure, and yet they contained large quantities of nitrogen and also enriched the soil considerably in this element. Where then had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Looking back over the papers, one can see how very close some of the older investigators were to resolving the mystery: in particular, Lachmann carefully examined the structure of the nodules, which he associated with the nutrition of the plant, and showed that they contained 'vibrionenartige' organisms. His paper, however, was published in an obscure journal and attracted little attention (Lachmann, 1891). Atwater in 1881 and 1882 showed that peas acquired large quantities of nitrogen from the air and later suggested that they might 'favour the action of nitrogen-fixing organisms'. But he was too busily engaged to follow the matter up, and once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

1.4 The beginnings of soil microbiology

It had been a maxim with the older agricultural chemists that 'corruption is the mother of vegetation'. Animal and vegetable matter had long been known to decompose with the formation of nitrates: indeed nitre beds made up from such decaying matter were the recognised source of nitrates for the manufacture of gunpowder during the European wars of the seventeenth and eighteenth centuries. No satisfactory explanation of the process had been offered, although the discussion of rival hypotheses continued until 1860, but the conditions under which it worked were known and on the whole fairly accurately described.

No connection was at first observed between nitrate formation and soil productiveness. Liebig rather diverted attention from the possibility of tracing what now seems an obvious relationship by regarding ammonia as the essential nitrogenous plant nutrient, though he admitted the possible suitability of nitrates. Way (1850, 1852) came much nearer to the truth. He showed that nitrates were formed in soils to which nitrogenous fertilisers were added. Unfortunately he failed to realise the significance of this discovery. He was still obsessed with the idea that ammonia was essential to the plant, and he believed that ammonia, unlike other nitrogen compounds, could not change to nitrate in the soil but was absorbed by the soil. But he only narrowly missed making an important advance in the subject, for after pointing out that nitrates are comparable with ammonium salts as fertilisers he writes:

> Indeed the French chemists are going further, several of them now advocating the view that it is in the form of nitric acid that plants make use of compounds of nitrogen. With this view I do not myself at present concur: and it is sufficient here to admit that nitric acid in the form of nitrates has at least a very high value as a manure.

It was not until 10 years later, and as a result of work by plant physiologists, that the French view prevailed over Liebig's, and agricultural investigators recognised the importance of nitrates to the plant and of nitrification to soil fertility. It then became necessary to discover the cause of nitrification.

During the 1860s and 1870s, great advances were being made in bacteriology, and it was definitely established that bacteria bring about putrefaction, decomposition and other changes; it was therefore conceivable that they were the active agents in the soil and that the process of decomposition was not the purely chemical 'eremacausis' Liebig had postulated. Pasteur himself had expressed the opinion that nitrification was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Schloesing and Müntz (1877, 1879, 1882) during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took 8 days to pass. For the first 20 days, the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column, and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of 20 days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to micro-organisms – 'organised ferments', to use their expression.

Warington (1878, 1879, 1884, 1891) had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society, he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms, in spite of some years of study,

Table 1.4 Relationships between nitrogen supply and plant growth.

Nitrogen in the calcium nitrate supplied per pot, g	None	0.056	0.112	0.168	0.224	0.336
Weight of oats obtained (grain and straw, g)	0.390	5.680	10.961	15.007	21.357	30.175
Weight of peas obtained (grain and straw, g)	3.093	2.137	7.725	5.619	8.186	11.352

Source: From Hellriegel and Wilfarth (1888).

by the gelatin methods then in vogue. However, Winogradsky (1890a–c) isolated these two groups of organisms, showing they were bacteria. He succeeded where Warington failed because he realised that carbon dioxide should be a sufficient source of carbon for them, so that they ought to grow on silica gel plates carefully freed from all organic matter; and it was on this medium that he isolated them in 1890.

Warington also established definitely the fact that nitrogen compounds rapidly change to nitrate in the soil, so that whatever compound is supplied as manure, plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants; in natural conditions, they take up nitrate only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous nitrogen has from time to time been revived, but it is not generally accepted.

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of experiments in sand cultures, Hellriegel and Wilfarth (1888) showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied – the duplicate pots agreeing satisfactorily – while in the case of leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed, the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This stagnant period was not seen where nitrate was supplied. Results from two of their experiments are given in Table 1.4.

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than that originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to 0.910, 1.242 and 0.789 g per pot, respectively. They drew two conclusions: (1) the peas took their nitrogen from the air and (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation, they connected two facts that were already known. Berthelot had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the roots of Leguminosae contained bacteria. Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts:

1. In the absence of nitrate, peas made only small growth and developed no nodules in sterilised sand; when calcium nitrate was added, they behaved like oats and barley, giving regular increases in crop for each increment of nitrate (the discordant results of Table 1.4 were obtained on unsterilised sand).

2. The peas grew well and developed nodules in sterilised sand watered with an extract of arable soil.
3. The peas sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments. At a later date, Schloesing and Laurent (1892) showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil and thus finally clinched the argument. The organism was isolated by Beijerinck (1888a–c, 1989) and called *Bacillus radicicola*, but is now known as *Bradyrhizobium*.

Thus, another great controversy came to an end, and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert and Pugh was cleared up. The laboratory experiments gave the result that leguminous plants, like non-leguminous plants, have themselves no power of assimilating gaseous nitrogen; this power belongs to the bacteria associated with them. This result was obtained because by excluding all traces of organic matter, and thereby ammonia, from the soil, the apparatus and the air, there was no chance of infection with the necessary bacteria and no assimilation could occur. In contrast, in the field trials the bacteria were active, and there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by Wollny and Berthelot. It was supposed to be proved by Laurent's experiments. He grew buckwheat on humus, obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil), good growth took place. The experiment looks convincing, but is really unsound. When an organic-rich soil is heated, some substances are formed that are toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin.

1.5 The development and application of modern knowledge of soils

Our understanding of the physical, chemical and biological factors that control the fertility of soils has advanced greatly since the time of Gilbert and Lawes. The application of this knowledge has resulted in great increases in productivity. The most useful gains have been from new understanding of the storage and movement of water in soils, the value and valuation of reserves of plant nutrients, the physical, chemical and biological conditions in the rhizosphere, and from the role of cultivations in modern production systems. Both research and its application have been greatly aided by developments in the basic sciences, in optical and electronic instruments and in computers. Experimental work in the field with crops provides a practical assessment of advances in exploiting basic soil studies. In this context, the experimental designs initiated by R. A. Fisher proved to be invaluable by providing methods of solving problems in soil management and cropping systems which could not be attempted before. The development of statistical methods of assessing error in biological experiments was also a major advance. Field experimentation became a major technique in research on soil fertility and, because the precision of the results could be estimated, they were readily accepted by other scientists. Designs in which several factors were tested simultaneously – and their interactions measured – were an important advance. They opened the way to multidisciplinary research; for example, the effects of biological, physical and management factors on crop nutrition were then widely investigated.

During the twentieth century, agricultural research became recognised as important to national interest and attempts were made to bring some organisation and funding to research. For example, in the UK the Agricultural Research Council was established in 1931, and while it has changed its focus and remit, parts of the original aims of the Council are still within the much broader remit of the Biotechnology and Biological Sciences Research Council. The application of the research to develop agriculture was given to the newly established National Agricultural Advisory Service (NAAS) in 1946. This government-funded body later became the Agricultural Development and Advisory Service (ADAS) in 1971 and in 1997 was privatised. It now has a remit well beyond its original focus in agriculture as a provider of environmental solutions, rural development services and policy advice. This pattern of government-funded support for guidance in land management being progressively privatised is not unique to the UK and is now a common pattern in large parts of the western world.

Internationally, agricultural research to aid food production and agricultural development in less developed parts of the world has developed under the Consultative Group for International Agricultural Research (CGIAR). CGIAR has established research centres around the world which have in some cases a specific crop focus (e.g. the International Rice Research Institute, IRRI) and in others a regional agricultural focus (e.g. the International Centre for Research in the Dry Areas, ICARDA). These centres have provided a well-resourced focus for international collaboration on agricultural research issues.

1.5.1 Advances in soil science

Developments in our knowledge of soil science will be made clearer in the succeeding chapters of this book. Important advances were made last century resulting from the application of new methodologies, such as X-ray and spectrographic analyses, which led to our understanding of the crystalline structures of layered aluminosilicate minerals and information on the distribution of micronutrients.

Work on the forms of nutrient reserves in soils, their mobilities and availabilities, and the fate of nutrients applied in fertilisers continued throughout the last century. Work on phosphorus was advanced when the radioisotope ^{32}P became available. Other advances were made by applying thermodynamic concepts to the solubilities of nutrient ions. Understanding of cation relationships took a notable step forward when Schofield's Ratio Law was proposed in 1947; later advances came from the use of the quantity (Q) and intensity (I) factors. Concepts of nutrient ion mobility, first developed in the USA, were used in the mathematical modelling of processes of nutrient uptake by Nye and Tinker (1977) and subsequently by Barber (1995). These models of nutrient processes in soil have become the basis for management of nutrients in farming systems.

Much research has been done on the role of nitrogen in soil/crop systems. This is justifiable as, in many conditions, the supply of nitrogen has a greater effect on crop performance than do the supplies of other nutrients, so that on the world scale this nutrient dominates fertiliser markets. In past years, there was a period in which only about 30% of the nitrogen applied was, on average, taken up by the crops grown. The 70% that was not recovered represented a serious loss to farmers and was also the cause of environmental pollution – nitrate leached into waters used for public supply and nitrous oxide formed by denitrification contributed to greenhouse gas emissions and damage to the ozone layer of the lower part of the stratosphere. Improved technologies, including the use of the stable isotope ^{15}N, have made it possible to show in experiments that up to 90% or more of the nitrogen applied as fertiliser can be accounted for in uptake by the crop plus that nitrogen stored in the soil which may benefit future crops. Through improved nitrogen management, we are in sight of securing much higher efficiency of fertiliser nitrogen applied to crops, ranging from wheat in Europe to rice in Southeast Asia. The investigations described previously of the roles of micro-organisms in the fixation of nitrogen by leguminous crops have led to methods of preparing cultures of the organisms (*Rhizobium* spp.) which are specifically associated with particular legumes. These cultures have been made available to farmers for inoculating crops which are to be grown on soils where the appropriate species of *Bradyrhizobium* is lacking.

The management of other major nutrients, notably phosphorus and potassium but also calcium and magnesium, has been greatly aided by studies of the soils and crops in long-term experiments. The classical experiments at Rothamsted begun by Lawes in the nineteenth century have been invaluable in these studies; they have shown that reserves of phosphate and potassium accumulated in soils from fertiliser additions have considerable value in crop production. Long-term experiments also provide the best basis for relating soluble nutrients in soils to crop performance and to the need for fertilisers; they also lead to calculations of nutrient cycles which are essential for the efficient management of crop nutrition. Increasingly, the records provided by long-term experiments have provided both the underpinning knowledge to build models of how the soil system operates (for instance the Rothamsted Model of Soil Carbon, see, e.g., Jenkinson (1988) and Chapter 4 in this volume) and the data for the testing of model simulations.

The management of soil has been much improved as a result of scientific work. The cultivations necessary for good crop growth have been defined; minimum cultivation systems lessen the energy required and conserve soil structure and soil organic matter. Erosion of the cultivated layer of soil by water and by wind is a serious threat to efficient agriculture in many parts of the world. Studies of the mode and extent of losses of soil under practical conditions have led to recommendations for improved management of cropping systems which avoid these losses. Another serious hazard is the damage done to plant growth, and also to soil structure, by the salts which accumulate in saline soils. Salinity may occur naturally, or it may be the result of irrigating with unsuitable water. Investigations of this problem have led to definitions of the water quality that is required to remove soluble salts in drainage and to the use of gypsum for reclaiming saline soils. With good quality irrigation water and correctly managed drainage, salinity need not now be a problem for efficient crop production.

1.5.2 Soil surveys

The first proposals for the classification and mapping of soils were made by Russian workers in the middle of the nineteenth century. Surveys were made in Southeast England at the end of the nineteenth century, with other local surveys made early in the twentieth century (see, e.g., Kay, 1939). While the practice of soil survey has been widely undertaken in many parts of the world, Great Britain provides an example of many of the trends which have occurred. Soil mapping was undertaken principally in the period of 1945–1990 when maps on the scale of 1: 250 000 were produced across Great Britain and maps at scales of 1:63 360 and 1:25 000 were also produced for some areas. As part of the link between soil survey and agriculture, land capability maps were also derived. These maps use soil survey data, climate data and landscape data to show the limitations exhibited by areas of land for arable agricultural production. They had their origins in the USA and where an eight-class system was first introduced by USDA in 1961 (Klingebiel and Montgomery, 1961), with subsequent modifications for use in the national contexts; for example, Bibby and Mackney (1969) produced a modification of the USDA scheme for application in Great Britain with seven classes. In all systems, Class One land is land with no limitations and high potential productivity for arable crops. Class Two land has some minor limitations for arable agricultural production which limits the choice of crops and may restrict timing of cultivations (e.g. moderate or imperfect drainage and less than ideal rooting depth and moderate slopes). Class Three land exhibits moderate limitations which restrict the choice of crops but is still considered suitable for arable production with appropriate and good management. Class Four land is considered to have moderately severe limitations (e.g. poor drainage, shallow and/or very stony soils, etc.) which restrict choice of crops and need very careful management. Land in lower classes is not considered suitable for other than low productivity agricultural uses and non-agricultural uses such pasture, forestry and recreation. Most land capability systems identified subclasses of Classes Two to Four, where the major limitations to agricultural production were identified. These often included limitations due to drainage, erosion, wetness, climate and specific soil limitations. For specific discussion of land capability in relation to soil fertility, see Section 3.2.1.

Today in Great Britain, there is now no systematic mapping programme. The few soil surveys undertaken are for specific purposes, but databases containing soil information derived principally from earlier soil survey work and information gathered for specific tasks are available and can be interrogated.

One of the key contributions of soil surveys and soil classification was in the context of ‘technology transfer’. Technology transfer involves combining information about soil properties gained from soil survey with the results of experimental work at that site to provide guidance on land use such as fertiliser recommendations; this knowledge is transferred to a distant site where the soil classification is the same. In addition to soil maps, advisers require computer-based information services giving the capability for cropping and physical, chemical and biological properties of the soil. Such information is becoming essential to modern management systems which aim to promote the productivity of soil. On a world scale, the most widely used tool for technology transfer is probably the *Soil Taxonomy* (1999) system developed in the USA. More recently, under the auspices of the International Union of Soil Science, the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) has been introduced. While soil surveys are still undertaken, there have been rapid changes in the manner in which soil data are recorded and managed. A recent significant shift has been the management and presentation of data using digital soil mapping.

The IUSS Working Group on Digital Soil Mapping (WG-DSM) defines ‘Digital Soil Mapping’ as ‘the creation and the population of a geographically referenced soil databases generated at a given resolution using field and laboratory observation methods coupled with environmental data through quantitative relationships’. In addition, data may be added through inferred spatial and non-spatial relationships between soil and other environmental properties. The development of pedometrics (the application of statistical and mathematical methods for the study and understanding of soils, their distribution and development) has greatly enhanced the development of digital soil mapping.

DSM can rely upon, but is distinct from, traditional soil mapping or soil survey which involves the manual delineation of soil boundaries by field soil scientists. This digitised and georeferenced soil survey information does not become DSM until the Geographical Information System layer is used to derive other soil-related information within a GIS or similar information software application.

Digital Soil Mapping makes extensive use of previously collected soil survey data and progress has been considerable because of rapid development in computing and the increasing ease with which data are gathered and managed electronically.

1.5.3 Precision Farming

In recent years, as the costs of fertilisers and other agrochemicals have increased and there have been increasing controls on agriculture in terms of leaching of fertilisers, nutrients and pesticides to water courses and groundwater, there has been a shift towards precision agriculture or precision farming. Precision agriculture, or information-based management of agricultural production systems, has developed over the last two decades and is based on the recognition that soils and crops will vary within a field. Initially the focus was to adapt fertiliser distribution to varying conditions across a field, but increasingly with the increased use of new technologies such as global navigation systems and geographic information systems has resulted in a much wider set of applications. Initially these uses were extended to the effective and efficient use of other agrochemicals such as herbicides and pesticides and the correct timing and placement of irrigation water, but with time other practices have evolved such as automatic guidance of agricultural vehicles and implements, autonomous machinery and processes, and product traceability and software for the overall management of agricultural production systems. One consequence is that there is much more efficiency in the use of resources for crop production such as fertiliser, irrigation water, pesticides, etc. This is in sharp contrast to earlier practices where the same fertiliser or pesticide rate was applied to the whole field, often focusing on higher levels of application to address the demands of the poorer soils within that field, with a consequent over application in some parts of the field. This resulted in poor use of valuable resources and often resulted in environmental damage. While early approaches of precision agriculture were based on traditional soil survey maps and the expertise of the farmer, the availability of new technologies – such as global positioning systems, digital soil maps, remote and proximal soil and crop sensors, satellites or other aerial images – and information management tools such as geographical information systems to assess and understand variations has radically changed the practice of precision farming greatly increasing the precision of placement of the agrochemicals and other external resources. The increasing availability of digital soil maps and soil information now provides a wealth of information which is a further contribution to the efficient and effective management of resources. These various sources of information integrated with agricultural machinery, which is able to place agrochemicals and other crop needs to a high degree of resolution, has radically changed the amount of agrochemicals used in a field, introducing economic and environmental benefits as a result of better placement. Precision agriculture enables the efficient use of resources which provides cost savings and assists in the reduction of environmental damage. Gebbers and Adamchuk (2010) have briefly reviewed the considerable impact the use of precision agriculture has had on food production and food security.

Table 1.5 Fertiliser use in arable and grassland in Great Britain 1998–2010 (kg/ha).

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total N	126	125	123	116	117	113	110	109	107	105	95	97	102
Total K_2O	45	42	40	37	40	36	37	35	34	32	27	22	25
Total P_2O_5	35	32	32	29	31	28	28	27	25	24	20	15	19

Source: From DEFRA – http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-environ-fertiliserpractice-2010.pdf.

1.5.4 Fertilisers

The global use of fertilisers expanded greatly during the twentieth century and the first years of the twenty-first century, resulting in large increases in crop yield. According to Cooke (1982), global use of N, P and K fertilisers by 1913 was 1.4, 0.9 and 0.7 Mt, respectively. By 1998, the consumption had increased to 82.1, 14.2 and 18.0 (FAO, 2010). By 2007, the total global consumption of fertilisers was estimated at 179 Mt (FAO, 2010). These increases have resulted from the application by farmers' advisers of the research work which has identified the deficiencies of the main nutrients in soils and crops.

Both in the world as a whole, and in the UK, the amounts of nitrogen used dominate compared with applications of other nutrients; this nutrient is responsible for the major part of the cost of fertilisers to the world's farmers (in the UK about three-quarters of the total spent on fertilisers is for nitrogen). The extent to which farmers change their fertiliser practice on particular crops is shown by the *Surveys of Fertiliser Practice* which were initiated in the 1940s and still continue. Similar surveys are made in a few other countries. While fertiliser use during the twentieth century showed a steady increase in the amount used per hectare, data on the use of fertilisers in Great Britain between 1998 and 2010 show a pattern of a 'levelling off in use' and, in the most recent years, an overall reduction in the amounts of N, P and K applied per hectare of land (Table 1.5). In part this can be ascribed to our increasing knowledge about crop management and increased precision in fertiliser management, but the introduction of regulations enforcing nitrate-vulnerable zones have had a major effect (see DEFRA, 2011).

1.5.5 Ecosystem services

The publication of the Millennium Ecosystem Assessment (2005) brought the concept of ecosystem services to the fore. These services were broadly defined as 'provisioning services' such as food and water; 'regulating services' such as regulation of floods, droughts, land degradation and disease; 'supporting services' such as soil formation and nutrient cycling and 'cultural services' such as recreational, spiritual, religious and other non-material benefits.

Soils are widely recognised as an essential part of natural and agricultural ecosystems. Increasingly it is recognised that the role of soils is key to the provision of ecosystem services. These ecosystem services play key roles in the functioning of the ecosystems of which the soil is a part, in both natural and managed production systems. Soils provide beneficial services through the roles played in soil formation, nutrient cycling and primary production. In some respects, the regulatory roles of soils provide key services to other components of