Experimental agronomic sciences

Memories from yesterday, hopes for tomorrow

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Agronomy becomes a science

According to the *Encyclopaedia Britannica* is a science “any system of knowledge that is concerned with the physical world and its phenomena and that entails unbiased observations and systematic experimentation. In general, a science involves a pursuit of knowledge covering general truths or the operations of fundamental laws.” In this systematic sense, agronomy may be called a science since about 200 years. The old Romans like Cato, Columella, Horatius or Plinius, up until writers living in the 18th century like – in Germany – Otto von Münchhausen or Johann Beckmann described agricultural practices. But only in the second half of the 18th century people like Reichart (Krug, 2004) started systematic experimentation, ordering our knowledge of the agricultural production systems, of the processes occurring and of the effects of human interference on these processes.

The scientific development of the ending 18th century was characterized by a rapid increase of our understanding of the basic natural processes. For example, Joseph Priestley (1733-1804) discovered in

1772 that air is not a uniform medium but consists from several gases. Nicolas-Théodore de Saussure (1767-1845) described some 30 years later his observations that plants take up CO_2 and release O_2. He also found that plant roots absorb salts, but this observation apparently was not fully realized by his colleagues at that time.

In Germany Albrecht Daniel Thaer (1752-1828) ought to be mentioned, a medical doctor from Celle in Northern Germany, who also had a good chemistry background and already knew that organic materials such as plants consisted of carbon, hydrogen, oxygen, nitrogen, phosphoric acid, alkali and other metals. However, he did not know the sources of these elements and compounds, and thus had no basis to assume that essentially minerals are taken up by the plant. He had to leave it to his student Philipp Carl Sprengel (1789-1859) to conclude in 1826 that the soluble salts in the humus extracts he had worked with were the real plant nutrients (van der Ploeg *et al.*, 1999). It is interesting to note that Liebig, who was well-known as an organic chemist, published for the first time in 1840 on agriculture, and sold the mineral nutrition theory as his own view, apparently much more efficiently than Sprengel. Sprengel also published the "law of the minimum" in 1838, two years before Liebig, to whom this law is being attributed (van der Ploeg e*t al.*, 1999).

Thaer himself adhered to the traditional humus theory. But although he had a wrong idea on the exact chemical nature of the substances needed for plant growth, his background in chemistry made him sensitive to the fact that plant nutrients, i.e. chemical substances, had to be provided to the crops. After approximately one century, Central Europe had recovered from the thirty-year war, and a strong population growth characterized the ending 18^{th} and beginning 19^{th} centuries. For example, in Lower Saxony, the area in which Thaer lived, the population in the second half of the 18^{th} century was around 1.5 million and increased by 20% until 1821 (Könenkamp, 2002). The gap between cereal supply and demand increased resulting in a massive cereal price increase. On the other side, the traditional land rights gave no room for yield increases. The farmers were invested with land by noble or ecclesiastical landlords. Since the fields were small and hardly any road infrastructure existed, all winter fields of a village were pooled and cropped in the same way. The individual farmer had no decision power on what to crop on his land.

The traditional cropping system was since the middle age a three-field rotation. The fallow field and the communal land was grazed by all members of the village and the landlords had also grazing rights on the fallow. Nutrients were imported into the farming system from natural ecosystems by grass sods and tree litter. The manure of the animals remained in the field, very unevenly distributed i.e. with high nutrient concentrations on a few points, where losses over winter were high, whereas the vast majority of the area did not get back the nutrients exported through harvest.

The cropping systems were clearly nutrient limited. As will be shown below, in later times this problem was dealt with in a typical reductionistic manner: the solution to this limitation was simply sought by adding fertilizer nutrients to the soil up to the demand of the plants. However, this was not so easy since nutrients could not be imported easily into the farming systems. Thus, the system had to be changed on the farm level. Thaer's "system approach" proposed measures to improve primary production, import nitrogen from legumes, and reduce nutrient losses, in particular through:

– summer-cropping of the fallow (improved three-field rotation)
– extension of forage crop production
– increasing animal stocking rate and stable keeping
– alternating broadleaved and cereal crops
– using new, higher yielding crops.

Thaer was not the first one to recognize the limitations associated with the traditional three-crop rotation. For example, Johann Christian Schubart (1743-1787) a practical farmer, wrote a book in 1784 in which he criticized fallow, grazing and grazing rights of the landlords as "plague of agriculture". Thaer, however, systematically identified and ordered the knowledge of agriculture available in his time and made a science from it. As discussed before, this systematic structure is the nature of science. Having come from medicine, he approached agriculture with the rationalistic view that the title of one of his books suggests, "Fundamentals of rational agriculture". Today we would call his perspective a "systems view". He viewed the farm as an organisation similar to a factory, both farm and factory aiming at producing goods using production factors. He identified labour, capital, soil and intelligence as production factors in agriculture. These are applied to the cropping or field system, which is integrated into the farm as the economic unit which has to be optimised.

This approach implied two important methodological facts. Firstly, Thaer treated agriculture as a system with a hierarchical order analogous to other, industrial production systems, and secondly he attempted to quantify the system components. Feller *et al.* (2003) show very nicely how he quantified the fecundity of soils and the effects of manuring and removal of fertility through harvest.

Agronomic science begins to specialize

Despite improvements in rotation design, mainly by inclusion of legumes, the agricultural systems of the 19th century were nutrient-limited. This situation changed following the acceptance of the mineral theory, through the imports of Chile saltpetre (the first imports of saltpetre from Chile came to England in 1830) and guano, the production of superphosphate (in 1843 John Lawes brought superphosphate on the market) and the mining of potassium during the 19th century. It was, however, not clear whether the addition of mineral nutrients alone was sufficient to ensure crop growth. To find out whether soil fertility could be maintained in the long run with mineral fertilizers alone, long-term experiments were initiated. The first one was set up in Rothamsted by John Lawes and Henry Gilbert in 1843 to find out whether “mineral manure” (P, K, Na, Mg) is sufficient for plant growth. In the first instance they followed the theory of Liebig that nitrogen was taken up from the air and not necessary to supply to the soil. But after three years already they disproved this theory and added ammonium sulphate to their mineral treatment (Jenkinson, 1991). Long-term experiments became widespread in the 19th and early 20th century. Alone Lawes and Gilbert initiated more than a dozen of them (Jenkinson, 1991 ; Poulton, 1996).

Another agricultural dicipline emerged from agronomy in the middle of the 19th century, i.e. plant pathology. In Germany, Julius Kühn (1825-1910) working with cereal smut and Anton de Bary

(1831-1888), working with potato blight identified fungi as the causal agents of these plant diseases.

Progress in agricultural science in the early 20th century was mainly characterized by the rediscovery of the Mendelian laws, leading to the production of new varieties through systematic crossing and selection, and by the Haber-Bosch ammonia synthesis which made nitrogen fertilizers available in large quantities. The increased use of the combustion engine pushed farm mechanization and made deeper soil tillage possible. But the new developments also had their critics. First it was Rudolf Steiner (1861-1925) who, upon request of farmers in Silesia, developed what was then called the bio-dynamic agriculture. The pace of changes in agricultural production in the second half of the 19th century had been, compared to the past, breathtakingly rapid and farmers were suspicious whether the new production techniques were really sustainable. What Steiner developed in 1923 was a truly holistic approach not only by seeing close ties between human life and agriculture, but also by relating biological processes to cosmic constellations.

The idea that organic plant growth is part of a matter cycle of growth and decomposition was also pursued by Sir Albert Howard (1873-1947) and Lady Balfour (1899-1990). Common to all three, Steiner, Howard and Balfour is their holistic view which was in contrast to the trend of increasing specialisation and reductionism in science. The mainstream agricultural science investigated a plant disease problem as an interaction between two organisms and a plant nutrition problem as a deficiency or surplus of an individual nutrient, whereas for the proponents of "organic" agriculture these were problems of system imbalances.

The specialisation of agronomic science into the sub-disciplines that had emerged between the beginning of the 19th and the beginning of the 20th century made agronomists wonder what the role of "agronomic science" could be. The domains of plant breeding, plant pathology or plant nutrition could clearly be defined, but in this concert of specialists who had convincing successes in their fields it was found increasingly difficult to define the scientific domain of the generalist agronomist.

Agronomic science in the second half of the 20th century was characterized by enormous progresses in the development of agrochemicals, synthetic herbicides, large-scale development and use of fungicides and insecticides and hybrid breeding. In the 1960s, the green revolution brought about by international agricultural research centers increased yields worldwide, but was also accompanied by negative ecological side-effects like nutrient contamination of aquifers, pesticides being carried over into natural ecosystems, enormous energy consumption, overuse of water resources, etc. This led to a revival of organic agriculture in the 1970s. In the meantime world population grew and food security remained an issue, despite the tremendous production increases of the last 50 years. Globally, cereal production has doubled over the past 50 years as a result of improved varieties and increased use of fertilizers, particularly nitrogen, water and pesticides (Tilman *et al.*, 2002). However, cereal yields seem to more or less plateau off in the last ten or so years. An additional problem is that with increasing yield level input efficiency decreases.

Agronomy as a systems science

At the beginning of the 21st century and 200 years after de Saussure and Thaer the world has not only increased its agricultural production tremendously, but also its population and the demand of every individual with respect to natural resources. This constitutes at the same time challenges to agronomic science. Of course it is hard to predict to what degree the expected problems will occur and how we will be able to solve them. However, we have good reasons to assume that food security will continue to be a major challenge to agronomists as will be the sustainability of our intensive crop production. I will touch these objectives only briefly and would like to concentrate on the last point of this list, the development of our science discipline so that we can improve food security and the sustainability of our production.

In its study of the development of food requirements and production over the 25-year period 1995-2020, the International Food Policy Research Institute predicted an annual increase of the world population of 73 million people reaching roughly 7.5 billion in 2020

(Pinstrup-Andersen *et al.*, 1999). In order to meet the food demands of the increased population and the increased demand for meat which is due to the increased purchasing power of the people in many third world countries, particularly in Asia, world cereal production will have to rise by 40% in 2020 compared to 1995.

Since practically all the land suitable for agricultural use is already used for agricultural purposes, meeting this increased demand means increasing yields per unit area. To achieve this in a sustainable way an intensity increase is required, particularly in the productive areas of the world. These are not necessarily in the same regions where the people live. We therefore need a global land management where optimisation of resource use efficiency is a criterion as important as yield level and produce quality. Resources particularly critical in this respect are plant nutrients and water, but also soils. Low efficiencies of these resources mean inevitably pollution and degradation. Lastly, efficient ways of pest and disease control, or better regulation, also are urgent requirements to get out of the pesticide spiral.

But although food is the primary goal of agricultural crop production, the requirements of industrial societies comprise energy and raw materials for industrial use as well. This will result in more diverse crop production systems and landscapes. Increasing biodiversity in the crop subsystem most likely results in increased biodiversity of other organisms groups likely to result in reduced pest in disease pressure. Thus, meeting additional demands of highly developed civilisations can well go along with increasing sustainability. The latter is also possible with respect to the highly debated biotechnology. What is common to all these problems is the importance to analyse them at the appropriate systems level and to develop solutions at the same level by integrating all the lower levels.

This addresses the most important problem for agronomy, namely the identity of this science discipline. Agronomy is a systems science. We are not only dealing with the understanding of individual phenomena, but our aim is to understand highly complex systems in order to manage them. Therefore a crucial part of our science is to define the systems in an appropriate way, i.e. such that we get the right answers to our questions. In order to find out how our systems behave we usually make models with which we can run scenarios.

Systems may be considered hierarchically organized, in the case of agronomy from the molecule up to the globe. The lower levels are components of the higher levels and can therefore partially explain the phenomena on the higher levels. Agronomic management typically occurs on the plant or the field level, but for the solution of some of our environmental problems landscape management may be necessary. When it comes to policy issues even higher systems levels have to be considered. Traditionally, agronomists dealt with issues on the plant and field level. In the 1960s, agronomists wanted to understand more about the processes of yield formation in the plant and discovered crop physiology. In the 1980s and 1990s environmental issues were more prevalent which led many agronomists to look at phenomena in the agro-ecosystem or even on the landscape level. As agronomy was developing into higher systems levels, plant sciences discovered more and more processes at the lower levels, with a strong emphasis on molecular biology. The challenge to agronomists is to make use of the tremendous increase in knowledge at the molecular level by developing appropriate methods for systems integration.

Considering agronomy as a systems science and becoming aware of the importance of the systems definition at the appropriate level may help to get relevant answers to our questions. A simple example to illustrate this arises from the question: what fertilization strategy is most likely to ensure a sustainable production? Traditionally agronomists were analysing this problem at the field level over short time scales, e.g. by calculating annual nutrient balances of individual crops as we have seen in Thaer's example before. This was perfectly all right in the situation of under-fertilization because the effects of under-fertilization could be observed at the field level in terms of yield. The effects of over-fertilization, however, become apparent e.g. on the river catchment level where also longer time scales are relevant. Moreover, nutrient fluxes may be influenced not only by fertilization to the individual crop, but to the crop rotation. All this means, that the appropriate systems level definition for the question on optimal fertilization strategies under conditions of nutrient surplus may lie at the landscape rather than at the crop level.

Thaer also treated agriculture as a systems science. He frequently used the word "system" to indicate such complex structures. He also tried to quantify the effects of individual agronomic measures like fertilization. But his system boundaries were the agricultural farm. This was rational since, as mentioned before, agronomic interference had effects mainly on the farm, in terms of crop yields and farm income.

Nowadays the scope of agriculture has widened and our societies look closely on the income transfers to farms and the environmental impact of farming. So, the public discussion and the work of many agronomists already take place less at the farm than at the ecosystem level. The objectives are no longer that much categories of individual economic success, but ecosystems services. And the Danish ecologist Jacob Weiner (2003) predicts that "in the future agriculture will be understood as a form of ecological engineering: the manipulation of populations, communities and ecosystem for human purposes".

Which methodology is available to find out how agronomic systems perform in relation to changes of the external, e.g. climatic conditions, or human interference through agronomic measures like tillage, fertilization, irrigation, etc. These systems are complex and therefore difficult to test experimentally, especially at the ecosystem level. The combinations of external variables are close to infinite and therefore ways have to be found to do cheaper and faster experiments than field experiments. Since "science is about the correspondence of ideas with the real world" (Thornley, 1980) we also need to find ways to test hypotheses of systems behaviour. To reduce a large, complex system models are constructed, which are simplified representations of the reality. A comparison of the model's theoretical prediction with the reality, which can be a practical farming situation or a field experiment, tells us how adequate our understanding of the systems is. Agronomic modelling started in the 1960s and first tried to integrate the yield formation processes, in the beginning under nutrient and water unlimited conditions. Later, effects of water and nitrogen limitations were included, and in the 1980s cropping systems models were built which allowed to test rotations and to estimate nutrient losses or water consumption. A typical example would be the combination of a plant growth and a water balance model.

In the 1990s integrations were made up to the landscape level (Costanza *et al.*, 1993). But progress is also made towards the integration of the new knowledge from molecular biology. This issue has two facets. Firstly, there is hope that plant reactions can be better predicted when the genetic patterns are known. Secondly, crop models will play an increasing role in understanding the effects of genetic regulation, i.e. by predicting the effects of regulation at the biochemical level in terms of the performance of the plant or the crop (Hammer *et al.*, 2002 ; Stützel and Kahlen, 2004). How this could work has been demonstrated by Reymond *et al.* (2003) who related the three parameters of an ecophysiological model for leaf elongation to quantitative trait loci (QTLs) in a population of maize recombinant inbred lines, leaf elongation being well predicted on the basis of the presence or absence of QTLs.

Conclusions

Agronomy started off to become a science in our modern understanding some 200 years ago. It remained an experimental science over a good part of its existence, with relatively little theory building. Over its first 100 years agronomy dealt with nutrient-limited systems. System levels were field, cropping system and farm. Over time specialisation in agronomic science increased. The last 50 years have been characterized by nutrient surplus and by the intensive use of agrochemicals in the more developed parts of the world. The level of consideration became the field. Reductionistic, scientific approaches have led to big successes in yield improvement but they have had negative ecological impacts. What the world expects from us now is an intensification of the production by increasing resource use efficiency. This requires the integration of knowledge over several system levels. This means that we have to develop agronomy as a system science in which computer-based systems modelling becomes a central tool. Agronomy will remain an experimental science, but in the future many experiments will be carried out in the computer, thereby enlarging our theoretical understanding of the complex and fascinating issue of crop production.

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