

Concepts and practices of nutrient management in agro-ecosystems: Can we draw lessons from history to design future sustainable agricultural production systems?

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Konzepte und Praktiken von Nährstoffmanagement in Agrarökosystemen: Können wir aus der Vergangenheit lernen, um nachhaltige landwirtschaftliche Produktionssysteme für die Zukunft zu entwickeln?

1 Introduction

Agricultural production results in the transfer of nutrients from the soil to agricultural products. Nutrients are then transferred to humans either directly when plant products are consumed or via animal products. Ultimately a large fraction of nutrients ends up in animal and human wastes which may or may not be recycled in agricultural systems.

We distinguish three broad types of nutrient management in agricultural production systems. There are systems located on fertile soils in which nutrients exported by crops are being replaced by adequate application of fertilizers. Such systems are the most sustainable with respect to nutrient use and should be supported. There are systems in which nutrient inputs are much smaller than nutrient outputs by crops. These systems are observed in subsistence agriculture which is par-

ticularly widespread in tropical areas. In the short term, this “nutrient mining” leads to decreased crop production, to food insecurity and poverty, and in the long term to soil degradation which itself leads to further environmental degradation, food insecurity and poverty. Finally, in areas of intensive agriculture, especially in the presence of a large number of animals, nutrients are added to soils in excess to plant needs mostly in the form of animal manure. In these systems large quantities of nutrients imported on the farm as feedstuff end up in the animal excreta. This results in nutrient losses to water (P and N), to the atmosphere (N), and to the accumulation of pollutants in soils (e.g. heavy metals). Finally, it is now evident that some of the primary resources necessary for the production of fertilizers will become more difficult to acquire and therefore more expensive in the future (energy for N, rock phosphate for P).

Zusammenfassung

Ziel dieser Literaturstudie war es, die geschichtliche Entwicklung von Konzepten zur Nährstoffdynamik und -nutzung in Agrarökosystemen aufzuzeigen, das Erscheinen dieser Konzepte mit der Einführung von Nährstoffmanagementpraktiken in Verbindung zu setzen, und Strategien zu diskutieren, die eine bessere Nährstoffnutzung in der Zukunft ermöglichen könnten. In früheren Zeiten begrenzte Nährstoffmangel die Erträge und die landwirtschaftliche Produktion erheblich. Seit die theoretischen Grundlagen in Pflanzenernährung und Bodenkunde entwickelt worden sind und große Lagerstätten von Nährstoffen und fossilen Brennstoffen entdeckt worden sind, sind sehr große Mengen von Nährstoffen verfügbar geworden. Diese Ressourcen werden jedoch nicht nachhaltig genutzt. Moderne intensive, markt-orientierte Landwirtschaftssysteme zeigen häufig positive Nährstoffbilanzen, die zu Verlusten in die Umwelt führen, während negative Nährstoffbilanzen in der Subsistenzlandwirtschaft zu geringen Erträgen, Boden-degradierung, Nahrungsknappheit und Armut führen. Integriertes Nährstoffmanagement (INM) wird vorgestellt als notwendiger Ansatz zur verbesserten Nährstoffnutzung in landwirtschaftlichen Systemen und zur Verminderung von Verlusten an die Umwelt sowie als Komponente der ‚Doppelten Grünen Revolution‘, die eingeführt werden muss, um die Bedürfnisse zukünftiger Generationen auf nachhaltige Weise zu decken.

Schlagerworte: Stickstoff, Phosphor, Bodenfruchtbarkeit, Nahrungsproduktion, Umwelteinfluss.

Summary

The objectives of this review are to show how the concepts related to nutrient dynamic and use in agro-ecosystems changed with time; to relate the apparition of these concepts with the adoption of nutrient management practices; and to discuss strategies which could allow a better use of nutrients in the future. In early times nutrient deficiencies severely limited crop production. Since theoretical bases in plant nutrition and soil science have been established and since large deposits of nutrients and fossil energy have been discovered, very large quantities of nutrients have become available. These resources are however not used sustainably. Modern intensive, market-oriented agricultural systems often exhibit positive nutrient balances resulting in nutrients losses to the environment, while negative nutrient balances in subsistence agriculture lead to poor crop production, soil degradation, food insecurity and poverty. Integrated nutrient management (INM) is presented as a necessity to increase nutrient use efficiency in agricultural systems and to decrease losses to the environment and as one of the components of the “doubly green revolution” to be implemented to meet the needs of future generations in a sustainable manner.

Key words: Nitrogen, phosphorus, soil fertility, food production, environmental impact.

The objectives of this paper are 1) to show how the concepts related to nutrient dynamics in agro-ecosystems have changed with time; 2) to relate the appearance of these concepts with the adoption of nutrient management practices and the sustainability of agricultural production systems; and finally 3) to discuss strategies which could allow a more efficient use of nutrients in the future. For the sake of simplicity we divide history in four periods: the first period extends from the beginning of agriculture to the end of the XVIIIth century, the second period from the beginning of the XIXth century to the 1st World War, the third period from the 1st World War to the eighties, and the fourth period from the eighties to nowadays. This paper does not aim at presenting an extensive review of all aspects of nutrient dynamics. On the contrary, we have selected certain highlights of the past and of the present on which we base our recommendations for the future.

2 From the beginning of agriculture to the end of the XVIIIth century

This period was marked by the development of nutrient management methods through trial and error to improve crop yields. The basic scientific concepts started to be developed, but had little impact on nutrient management in practice.

2.1 Concepts

According to Aristotle, soil fertility was driven by “four qualities”: warmth, coldness, humidity and dryness (BROWNE, 1944), suggesting that plant productivity was more influenced by physical effects (humidity and temperature) than by nutrient inputs. The importance of animal manure and composts for improving crop production was however already well recognized (BROWNE, 1944). Pliny the Elder (23–79 AD) for instance mentions green manures and mineral manures such as ashes, nitre (KNO₃ and other nitrate salts) and marl (a mixture of clay and carbonate) as ways to improve crop production (see e.g. WINIWARTER and BLUM, 2008). Plants were also assumed to feed on organic material of related nature: olive stones were fed to olive trees, and vine shoots to vines (BOULAIN, 1989). Such beliefs and Aristotle’s theory were still influential during the Middle Age.

Words such as “sulfur”, “mercury” and “salt” were used by Paracelsus in relation to animal and plant nutrition but these terms had not the same meaning as nowadays. Similarly, the definition of the term “salts” used by PALISSY (1880) is very far from the definition we give to this term today (FELLER, 2007).

Van Helmont (1577–1644) looking for the “principle of vegetation”, was the first to establish a full mass balance in a pot experiment by measuring the mass of the tree and the soil at the beginning and after 5 years of experiment as well as the volume of water used for irrigation. Since he could not see any difference in the mass of the soil, he concluded that the water was the “principle of vegetation” and that the

soil could not be that principle (BOULAINÉ, 1996). In 1699, Woodward (1665–1728) showed that something from earth other than water was important to plant growth. And during the XVIIIth century theories and agricultural practices about plant nutrition were developed on the belief that plants relied directly on humus for their own carbon supply (FELLER et al., 2003).

2.2 Facts

Since the beginning of agriculture, animal manure, ashes, charcoal, marl and other wastes have been added to fields to increase yields and improve soil fertility (MEHARG et al., 2006; LINDERHOLM, 2007). In some cases these inputs were so high that they fundamentally changed soil properties. For instance in Northern Europe heather sod was used as bedding material for animals, and the sod-manure mixture was repeatedly brought back on sandy soils to improve yields of cereals. This practice resulted in the formation of deep nutrient-rich organic soils called plaggen soils (BLUME and LEINWEBER, 2004). Another example which has been discussed a lot during the last decade is the Terra Preta from Amazonia. The Terra Preta is a surface horizon rich in organic matter, charcoal, ashes and nutrients, overlying deep strongly weathered soils (LIMA et al., 2002). These soils were generated by pre-Columbian populations through the repeated additions of large amounts of organic wastes, charcoal, excrements and bones to the soils located around their settlements. Crop yields on the Terra Preta are about twice as high as those obtained on the adjacent non Terra Preta sites (GLASER, 2007). A specificity of these Terra Preta soils is the presence of very high amounts of charcoal, on average 50 t ha⁻¹ in the top 1.0 m of soil (GLASER, 2007), which increases nutrient (K, N, P) content and availability, cation exchange capacity, soil pH and water retention capacity.

Input-output nutrient balances have been calculated at the farm level for different periods covered by this section. Results shown by NEWMAN and HARVEY (1997) and OVERTON (2007) suggest that in the Middle Age in England P was more limiting for crop production than K or N. Only when enough animals were allowed to graze at large during the day and kept overnight on arable land where they deposited their dung, was it possible to avoid soil P exhaustion (NEWMAN, 2002). Similarly, fields located in the Nile valley had probably an equilibrated P balance during the Antiquity due to the sediments they received from the reg-

ular floods (NEWMAN, 1997). NEWMAN (1995) suggests that in the absence of external input the amount of P annually released through the weathering of the soil parent material and added from the atmosphere would amount to values ranging between 0.1 and 2.7 kg P ha⁻¹ year⁻¹. This would allow a cereal production of at most 0.5 t grain ha⁻¹ year⁻¹ which is in the lower range of yields observed in Europe during the Middle Age. BOULAINÉ (2006) also suggests that low cereal yields observed between 1700 and 1850 in France (circa 0.6 t grain ha⁻¹ year⁻¹) were the consequence of a generalized P deficiency due to constant soil mining without sufficient P restitution.

The increase in agricultural productivity observed in Southern and Eastern England from the XVIIth to the XIXth century, i.e. during the period qualified as “the English agricultural revolution”, needs to be commented here as it was achieved at least partly through an improved nitrogen management (OVERTON and CAMPBELL, 1996; OVERTON, 2007). According to OVERTON and CAMPBELL (1996), wheat yield increased during this period from 0.7 to 1.4 t grain ha⁻¹ year⁻¹. The most important modification in the agricultural production system was the full integration of animal and crop production. The cropping system which was before dominated by cereals and fallow, was replaced by the so called Norfolk four-course rotation including cereals (wheat), root crop (turnip, *Brassica rapa rapa*), another cereal (barley) and a temporary pasture including sown clover (*Trifolium* sp), while the proportion of surfaces under fallow strongly decreased. Such a rotation together with animal husbandry allowed indeed a much better use of nutrients. Clover could provide large amounts of N to the soil through biological fixation and, if sown in grassland, could strongly boost the production of grasses, providing large amounts of forage (NYFELER et al., 2009). Besides, as legumes acidify their rhizosphere they were able to solubilise soil P and make it available to other crops (LI et al., 2007). This mechanism might have been relevant in these probably low P soils. Significant quantities of these nutrients (N and P) were released after plowing the pasture and taken up by the following cereal with its extensive root system. The following turnip crop was able to take up nutrient from deeper soil horizons due to its tap root, limiting N losses by leaching and lifting other nutrients (P and K) located in deeper horizons to the surface. The turnip root provided forage and the leaves remaining on the soil contained nutrients that were then taken up by the next cereal crop. This rotation produced large amounts of forage increasing animal productivity and providing manure which

was recycled to the crops. The enhancement in crop yield was also connected with other aspects like soil drainage, the use of soil amendments (lime, marls), fertilizers inputs (ash, peat, turf, salts ...), crop and animal breeding, stall-feeding of livestock allowing a better use of manure, and on the structural level, to the change from the open-field to "enclosures" and to increase in farm surface (OVERTON, 2007; TURNER et al., 2001, WILLIAMSON, 2002). According to OVERTON (2007), these progresses were the results of trial and error experiments conducted by farmers. As KRAUSMANN (2004) notes for the transformation of preindustrial agriculture in Central Europe, the agricultural production system based on the Norfolk four-course rotation maximized local resource use efficiency. However this system had probably reached its limits and was not able to increase food production due to nutrient, especially P, limitation.

3 From the beginning of the XIXth century to the 1st World War

This period saw the development of the basic concepts in plant nutrition and soil science. However, given the lack of extension services, disputes between scientists and the lack of primary resources, these concepts could not be fully implemented in agriculture. Nutrient management remained during this period very much based on empirical observations and on trial and error approaches.

3.1 Concepts

After a long debate on the role of humus in plant nutrition (FELLER et al., 2003), Saussure in 1804 showed that most of the plant biomass was derived from the CO₂ of the atmosphere and that plant roots were taking up mineral salts in dissolved forms from the soil as a function of root size and activity and of salt solubility (ROBIN, 1998). Sprengel in the 1820s and 1830s refuted the humus theory, showed that plants required mineral nutrients such as N, P, K, Mg, and Ca for their growth and formulated the Law of the Minimum (VAN DER PLOEG et al., 1999). Based on these previous results and on own research LIEBIG (1840) definitively demonstrated that dry matter accumulation in plants was explained by the fixation of CO₂ from the atmosphere and the uptake of mineral nutrients from the soil solution. Afterwards Liebig became a strong promoter of the use of mineral fertilizers to compensate for soil nutrient depletion

in cropping systems (BLONDEL-MÉGRÉLIS and ROBIN, 2002). Liebig made however two errors (STICHER, 2004): first he thought that water soluble nutrients would be lost from the soil following rainfall and he proposed to add them in a vitrified form and second he affirmed that it was not necessary to add N fertilizers to crops as sufficient NH₄ could be delivered from the atmosphere.

Liebig's statement that no N fertilizer would be needed for crops was strongly disputed during the following decades. Gilbert and Lawes showed in the 1840s in field experiments conducted in Rothamsted in England that NH₄ fertilizers were essential to obtain high crop yields. Boussingault did between 1830s and 1870s extensive work on the N cycle measuring N contents in plants, soils, fertilizers, manure, water and the atmosphere and calculating N balance for crop rotations on his farm in Pechelbronn located at the foot of the Vosges in Eastern France (AULIE, 1970). Boussingault showed that plants took up more N than what had been added by fertilizers and that legumes could accumulate N from the atmosphere. He came to the conclusion that soils, legumes and manures could be significant sources of N for crops. These results were supported by those of Gilbert and Lawes and by those of Way who demonstrated that the amounts of NO₃ and NH₄ in rain water were absolutely insufficient to cover plant N needs (AULIE, 1970). Boussingault later also showed that the mineralization of the soil organic matter produced first NH₄ and then NO₃ and that plant could take up N as NH₄ or NO₃. However Boussingault had not the necessary knowledge in soil microbiology to understand the processes controlling N transformations in soils (AULIE, 1970). The points of view of Boussingault and Lawes on the necessity of nitrogen inputs were never accepted by Liebig (WAKSMAN, 1942). Based on analyses done in 1841, Boussingault also showed that the amount of P and bases exported by crops were equivalent to the amount of elements brought by the farmyard manure (BOULAINÉ, 1996). He concluded from this that his crops did not need additional fertilizers. But by doing so Boussingault forgot something: since the pastures on which the cattle grazed were regularly fertilized with river sediments, the nutrients exported by his crops were indeed derived from the upper parts of the Vosges (BOULAINÉ, 1996). The results of Boussingault were strongly opposed by Ville in France. VILLE (1867) was among the most enthusiastic supporters of inorganic fertilization, he thought that manure was of no use for crop production and that all the plants could derive their N from the atmosphere (AULIE, 1970). The dispute between Boussingault and Ville on the origin of N in plants

lasted during a decade and had to be arbitrated by a commission of academicians (AULIE, 1970). GRANDEAU (1878) warned against Ville's assertions. As an advocate of mixed fertilization, he suggested that soil organic matter was vital for plant growth since it increased the solubilization of mineral nutrients and thus their "bioavailability" to plants. The concept of bioavailability was born. Liebig sent Grandeau a congratulatory letter expressing full agreement with this point of view (GRANDEAU, 1878).

Other decisive advances relevant to nutrient management were made during this period. WAY (1850) demonstrated the "power of soil to absorb manure" by studying the percolation of slurries through columns filled with different soils and substrates, opening the whole field of research on nutrient sorption on soil particles (STICHER, 2004). Soil analyses were developed during this period to assess the nutrient (P/K) availability to crops (DYER, 1894). In the area of soil biology, HELLRIEGEL and WILFARTH (1888) demonstrated that legumes could fix N_2 from the air when their roots were nodulated and Beijerinck in 1888 isolated the N_2 fixing bacterium from these nodules (PENNAZIO, 2005). By the end of the XIXth century Winogradsky discovered the microorganisms responsible for nitrification in soils (WAKSMAN, 1946). In 1885, FRANK published the first paper on the role of mycorrhizae for the mineral nutrition of trees, and the concept of rhizosphere was presented by Hiltner in 1904 (HARTMANN, 2005). In the field of plant physiology, the importance of micronutrients for plant growth was discovered by Bertrand and his co-workers (BOULAINÉ, 1995b).

In the area of fertilizer production the situation evolved rapidly as well. J. Murray made the first production of phosphate in 1816 by solubilising bones in sulfuric acid (BOULAINÉ, 2006). He named the product «superphosphate». The patent for producing superphosphates was taken in 1843 simultaneously by J. Murray and Sir J. Lawes, triggering the start of P fertilizers production in Germany and England. During the second half of the XIXth century superphosphates were produced from the limited phosphorite deposits discovered in Europe. At the end of the XIXth century and the beginning of the XXth century, large deposits of rock phosphates were discovered in North Africa and in the USA. Large deposits of elemental sulfur were also discovered allowing the production of H_2SO_4 . Another source of P became available at the end of the XIXth century: the Thomas slags. These were by-products from the process of dephosphatation of iron minerals. These slags were a very popular source of P and lime in Northern Eu-

rope and Eastern France. Large K deposits were discovered in Germany at the end of the XIXth century. Finally, in 1908 Haber filed a patent on the "synthesis of ammonia from its elements" and afterwards Bosch developed this synthesis at the industrial scale enabling large production of NH_4 from N_2 and energy (ERISMAN et al., 2008).

3.2 Facts

The following, taken from BOULAINÉ (1995a, 1995b, 1996, 2006) and from TURNER et al. (2001), shows how the strategies of fertilization evolved during the XIXth century in France and in England. Already at the beginning of the century all possible materials (ashes, algae, wool wastes, household wastes, night soil ...) were used as fertilizers. The importance of N fertilizers was well recognized, and fertilizers were added on the basis of their N content (BOULAINÉ, 1995a). The "noir animal" ("black animal": burnt milled bones used in sugar refineries) was largely used as a P fertilizer around harbors which were importing sugarcane from the colonies. Guano was also a highly appreciated fertilizer (CUSHMAN, 2005). In France, the inputs of nutrients in agro-ecosystems remained however overall much lower than the removal of nutrients by agricultural products. By the mid XIXth century the needs of fertilizer were theoretically and empirically recognized, but it was not possible to increase crop production because of a lack of raw materials. In England the "agricultural revolution" started in the XVIIth century continued till the mid XIXth century. New manure and artificial fertilizers (e.g. nitrate of soda and superphosphates) started to be used by the middle of the XIXth century in England (OVERTON, 2007; TURNER et al. 2001). Agricultural productivity remained lower in France than in England because the population pressure had been higher since a longer time in France, because France had not experienced the "English agricultural revolution" and also because French scientists recognized only in 1880 the interest of solubilizing rock phosphates in acids (i.e. to use superphosphates) to increase crop yield (BOULAINÉ, 2006). Afterwards P fertilization became widely practiced to the point at which P balances were equilibrated, but then N and K became the next nutrients limiting crop growth (BOULAINÉ, 1996). Altogether the average grain production of wheat in France went from values lower than $1 \text{ t ha}^{-1} \text{ year}^{-1}$ by the beginning of the XIXth century to $1.5 \text{ t ha}^{-1} \text{ year}^{-1}$ at the beginning of the 1st World War, while in the same period in England the average wheat grain production

had increased from 1.4 t ha⁻¹ year⁻¹ to about 2.2 t ha⁻¹ year⁻¹ (BOULAINÉ 1996; TURNER et al., 2001; BRANCOURT-HULMEL et al., 2003).

4 From the 1st World War to the eighties

This period saw a strong development of the scientific understanding of nutrient dynamics in soils and of plant nutrition. Based on this knowledge fertilization recommendations were issued and implemented in the practice. This led to a very important increase in agricultural production in industrialized countries and in areas of the developing countries where the “green revolution” had been successful.

4.1 Concepts

Incredible progresses has been made in soil science and plant nutrition and therefore in the understanding of nutrient cycles in agro-ecosystems since the end of the 1st World War. For instance, techniques based on the use of radioactive or stable isotopes were developed to trace nutrients first in soil/fertilizer/plant systems and later within agro-ecosystems. A large number of chemical extractions was developed to assess the bioavailability of nutrients and pollutants. Investigation techniques became more and more powerful allowing a greater insight in the speciation of elements. The mechanisms of element sorption and desorption on model minerals were largely elucidated and modeled. The importance of soil microorganisms on nutrient cycling was studied with classical microbiological methods. And the transfer of substances through the soil was understood and modeled. Among the many reviews written on the works done during this period, the reader can be referred to those published by HASEGAWA and WARKENTIN (2006), SPARKS (2006) and BERTHELIN et al. (2006). On the plant's side, impressive progress was also achieved. The concept of element essentiality for plants was defined by ARNON and STOUT (1939). The uptake of nutrients, their transfer in plant and their role were studied at the cell, plant and field levels (MARSCHNER, 1995). In brief, we attained a very good understanding of many specific processes. Models started to be developed for nutrient and water uptake by plants and for biogeochemical cycling of nutrients in soils and were integrated into models describing plant growth (FELLER et al., 2004). This knowledge was translated into fertilization strategies that were implemented for maximal

crop yield. This new information, together with the development of more productive plant cultivars, irrigation and drainage schemes and efficient plant protection strategies led to the “green revolution”. In the fifties and the sixties, Borlaug and his colleagues developed cereals resistant to diseases, early maturing and day length insensitive, with a high harvest index (i.e. including dwarfing genes) and highly responsive to fertilization (CONWAY, 1997). These impressive progresses led to the idea that any environment could be put under cropping and become highly productive provided that the adequate inputs would be delivered (GRIFFON and WEBER, 1996).

Negative aspects of agricultural intensification were at this time discussed in relation to human health and not in relation to environmental protection. For instance excessive concentrations of NO₃ in plant products and in drinking water were seen as dangerous for human health (ADDIS-SCOTT and BENJAMIN, 2004). And high concentrations of heavy metals in soils or sludge were perceived as a risk as they could affect human health through the food chain (MCBRIDE, 1989).

Two paradigms were developed to improve crop production in developing countries during this period. At first, similar strategies to those used in industrialized countries were adapted to the developing countries resulting in the development of the “green revolution” (CONWAY, 1997). In the 1980s, however, it was recognized that such strategies were not adapted to smallholders living from subsistence agriculture. Propositions were then made to grow crops adapted to their local environment (i.e. tolerant to high Al content), having high nutrient acquisition capacity and/or nutrient use efficiency, together with application of small amounts of fertilizers (MARSCHNER, 1995). During this period a lot of research was also conducted on green manure, e.g. through the introduction of legumes, as a way to restore degraded soils (GILLER, 2001).

4.2 Facts

In industrialized countries these developments were implemented in the agricultural practice thanks to the development of efficient agricultural research institutions, extension services and agricultural schools. Guidelines for crop fertilization were established based on the amount of nutrient that could be released from soils and on plant needs (WALTHER et al., 1994). In France and Germany, rates of P and K fertilization equivalent to several times the plant

needs were recommended for soils showing low to very low available P and/or K. Nutrients were added so that they would not limit plant growth. AUSTIN (1999) shows that wheat yield which was before the 2nd World War close to 2.5 t ha⁻¹ year⁻¹ in the UK, had increased on average by 0.11 t ha⁻¹ year⁻¹ to reach 7.5 t ha⁻¹ year⁻¹ in 1997, and that high amounts of N fertilizers (on average 185 kg N ha⁻¹ year⁻¹ at the end of the 1980's) were needed to realize this high yield potential. The development of intensive animal production units resulted in the importation of large amounts of feedstuffs on farm (e.g. soybean) and in an increased nutrient transfer to the soils through manure disposal. The nutrient content of manure was given very little consideration at this time. The "purifying power of the soil" was considered to be so strong that manure as well as sewage sludge and household refuses could be added in large amounts to soils. The agriculture of many industrialized countries showed high surpluses (higher input than output) of P and N in the 1980's and 1990's. Within Europe, SPIESS (1999) estimated N surpluses to vary between 330 kg N ha⁻¹ year⁻¹ in Holland in 1995 and 74 kg N ha⁻¹ year⁻¹ in Poland in 1993/94 and the P surpluses to vary between 38 kg P ha⁻¹ year⁻¹ in Holland in 1985/86 and 6 kg P ha⁻¹ year⁻¹ in Poland in 1994/95.

The broad distribution of high yielding cereals cultivars (rice, wheat and maize) within "packages" including fertilizers, pesticides and irrigation in the developing countries in the sixties and seventies has been called the "green revolution" (CONWAY, 1997). It had a tremendous impact on crop productivity and global food production. In the sixties from a total population of 3 billion persons about 1 billion did not get enough food. Now on a total population of 6 billion "only" 0.8 billion are suffering from a lack of food calories. The success of the "green revolution" was, however, not equally distributed. It had a lot of success in areas where farmers were ready to take risks in adopting new technologies and where working forces, water and fertile soils were available. These were mostly areas in East and South Asia. However, other areas with low fertility soils, little possibility of irrigation, limited working forces and subsistence farming like Sub Saharan Africa, the mountainous areas of south Asia, the Deccan plateau in India, North East Brazil, the Andean regions, as well as the hillsides in Central America were little touched by the green revolution (CONWAY, 1997).

5 From the eighties to nowadays

On the one side, this period saw strong developments in plant and microbial molecular biology, in agro-ecological approaches and in integrated approaches. On the other side, the relationships between agriculture, environment and human health became much better understood. In practice some countries took steps to limit the excessive use of nutrients in agro-ecosystems, but the lack of nutrients remains a very important problem in subsistence agriculture, especially in Sub Saharan Africa. Finally, the finiteness of fossil energy now clearly impacts nutrient use as large surfaces are being planted with crops for bio-ethanol production (agro-biofuels).

5.1 Concepts

The most important scientific advances done during the last two decades in relation to nutrient management in agro-ecosystems were in the fields of molecular biology and in agro-ecology (CONWAY, 1997; GLIESSMAN, 1998; DALGAARD et al., 2003). The advances in molecular biology make it now possible to assess soil microbial diversity and to link the presence of given microorganisms to specific nutrient transformations in soils. For instance, progress has been made on identification of genes coding for the different steps of nitrogen transformations by bacteria (N₂ fixation, nitrification, denitrification), and DNA and RNA coding for these genes and proteins can now be extracted from the soil and quantified (HAYATSU et al., 2008). Similarly, tools are becoming available for the identification of arbuscular mycorrhizal fungi (AMF) living in symbiosis with plant roots and for studying the influence of AMF alone or in communities on plant nutrient uptake and on the C budget of plants (JANSA et al., 2006). Besides, modeling efforts have been made to understand the dynamics of microorganisms in the rhizosphere and the role of root exudates on nutrient dynamics and uptake by plants (HUGUENIN-ELIE et al., 2003; SCHNEPF et al., 2008). Finally, the better understanding of the genetic control of nutrient uptake and use by plants will help to identify plants efficient in nutrient uptake and/or to develop plants able to take up nutrients from sources which would otherwise not be plant available (PATHAK et al., 2008; ZIMMERMANN et al., 2003).

Agro-ecological principles are applied at many levels (intercropping, rotation, agroforestry, soil preparation...) to

increase resource use efficiency. NYFELER et al. (2009) using an appropriate statistical design showed that grass-legume mixtures fertilized with 50 to 150 kg N ha⁻¹ year⁻¹ give a higher yield than pure grass or legume stands fertilized with 400 kg N ha⁻¹ year⁻¹. The authors explain this by the N₂ fixation by the legumes and by the complementary use of resources by the grasses and legumes (due e.g. to their different rooting depths). In other cases, when one member of the intercropping is very sensitive to competition, then intercropping can lead to a very strong yield decrease due to competition between plants for N and water (DAELLENBACH et al., 2005). Similarly, the processes underlying the effect of rotation, soil preparation and manure application on nutrient fluxes in the soil/plant system are becoming better understood (OBERSON et al., 2006; JANSA et al., 2006; ANKEN et al., 2004; SCHRODER et al., 2007). We believe that further knowledge development in this field and its implementation can bring about a big improvement in nutrient use efficiency in agro-ecosystems.

The other important conceptual advance made in the last two decades was the establishment of the links between environmental degradation and excessive or insufficient nutrient inputs in agriculture (SMIL, 2000; GALLOWAY et al., 2008). P can be lost from high P soils to water bodies, triggering eutrophication and negatively affecting water quality (SIMS and SHARPLEY, 2005). The volatilization of NH₄ from animal slurries and the release of NO_x from soil result in N deposition in neighboring ecosystems, triggering changes in the terrestrial/aquatic flora (UNEP/WHRC, 2007). Nitrous oxide (N₂O) is recognized as a glasshouse gas with a very high warming effect (UNEP/WHRC, 2007). Careless "recycling" of unsorted household refuse or sewage sludge results in strong increases in heavy metals and organic pollutants in soils, not only leading to pollutant accumulation in the food chain, but also having negative effects on soil biological activity. Similarly, the repeated applications of high rates of animal manure result not only in an accumulation of P and heavy metals in soils, but also in increased losses of elements and micro-organisms to the environment. We now realize that the soil fixing capacity for P can become saturated. P-rich soils have been named a "time-bomb", as they can release P to water over decades (FROSSARD et al., 2004). We also recognize that P and energy reserves are finite (SMIL, 2000). STEWART et al. (2005) recently showed that the reserves of rock phosphate that can be exploited at low cost might only last for a century, afterwards phosphate will become more expensive as it will have to be extracted from low quality ores or from mines which

are more difficult to access. In the last decades, laws or by-laws were also written in European countries for the protection of water and soil, and the first political strategies were developed to limit nutrient losses (MONTANARELLA, 2006; MENZI and GERBER, 2006).

This leads us to look not only at single processes but at the entire system (at the field, watershed, or landscape level (DALGAARD et al., 2003; FELLER and MARAUX, 2006)). For instance, to limit P losses to water, soil scientists must work with animal scientists (as fodder import on a farm is often the highest P input), economists (as losses have a cost for society), hydrologists, and of course with agronomists and farmers (SIMS and SHARPLEY, 2005). Modeling has become an indispensable tool to assess nutrient cycles and nutrient use efficiency in the different parts of the agro-ecosystem. Models can estimate nowadays not only nutrient uptake and plant growth but also nutrient losses from agro-ecosystems. Some models include even an economic component that allows testing the relationships between nutrient use, farmers' income and the external costs to be paid by society to mitigate the effect of nutrient losses (FELLER et al., 2004).

Tighter relations are also being established between nutrient cycling and human health. For instance, in some countries sewage sludge can not be recycled to agriculture anymore in the name of the precautionary principle as they may contain compounds which could affect human health (HERTER et al., 2003). Other nutrients (Fe, Zn, and Se) are gaining importance as we recognize that large numbers of people worldwide suffer from deficiencies in these elements. High quality crops should offer high amounts of these elements in a form that is available to humans (FROSSARD et al., 2000). Another change of paradigm is occurring as recent medical research suggests that NO₃ would not be as dangerous for human health as thought earlier (ADDISCOTT and BENJAMIN, 2004).

Studies conducted in the last decades in developing countries show that integrated approaches must be taken to solve the problems of soil degradation (VANLAUWE et al., 2006; TSBF-CIAT, 2005). One of these approaches is the "integrated nutrient management" (INM). INM aims at increasing nutrient use by crops and animals and at decreasing nutrient losses to the environment by considering all the components involved in nutrient cycling (climate, soil, plants, animals, and inorganic and organic nutrient sources) as well as the relevant socio-economic factors such as the production preferences of farmers, the food preferences of consumers, markets and trade policy (FROSSARD et al., 2007). Some examples of biophysical measures that can

be considered in INM schemes are: 1) increasing the input of exogenous nutrients, e.g. by increasing the use of fertilizers efficient in delivering available nutrients to plants, and/or by improving N input through N_2 biological fixation through the integration of adequate legume crops; 2) increasing nutrient uptake by plants through the appropriate timing and placement of organic and/or mineral fertilizer addition and through the use of crops with a high nutrient acquisition efficiency and/or a high nutrient use efficiency; 3) increasing nutrient recycling through the introduction of improved fallow or green manures and/or through proper reuse of animal manure and urban solid and liquid wastes; 4) decreasing nutrient losses by minimizing erosion, leaching, volatilization, denitrification and runoff.

5.2 Facts

In industrialized countries, total agricultural production has stabilized at a high level. In Europe ecological services of agriculture other than production are being recognized and begin to receive support. In Switzerland "direct payments" are given provided that farmers subscribe to a program including an equilibrated N and P balance at the farm level (CHAPPUIS et al., 2008). Farmyard manure is again recognized as a source of nutrients (and organic matter). In Switzerland taking manure into account in the fertilization plans has resulted in a 66 % decrease in mineral P fertilizer importations. The agro-ecological measures taken by the Swiss government contributed to the decrease in P concentrations recently observed in superficial water bodies (CORNAZ et al., 2005).

Energy becomes scarce so that the USA and European countries are producing increasing amounts of fuels from crop plants (MOL, 2007). This will have a strong effect on nutrient fluxes. For the US, FIXEN (2007) estimates that the production of maize for bio-ethanol on 4 million hectares which were previously not used for maize will increase the needs in N fertilizer by 760'000 t N year⁻¹ and in P fertilizer by 58'000 t P year⁻¹. He also estimates that planting biomass crops such as miscanthus or switchgrass (*Panicum virgatum*) on another 4 million hectares will require an additional 550'000 t N year⁻¹ and 58'000 t P year⁻¹. And finally he shows that the use of maize stover for bio-ethanol will result in the transfer of 80'000 t N year⁻¹ and of 13'000 t P year⁻¹ from maize fields to the refineries. Such increases in nutrient use can only result in increased nutrient losses. CRUTZEN et al. (2008) consider that the increase

in N_2O losses to the atmosphere to be caused by the increased N use will negate the global warming reduction aimed at by replacing fossil fuels by agro-biofuels. ANEX et al. (2000) estimate that the conversion of ligno-cellulosic biomass into ethanol through fermentation, the gasification of the remaining biomass, the recovery of NH_3 from the gaseous phase and the recovery of P and K in the fly ashes will allow to recover a large fraction of the nutrients added as fertilizer to produce the switchgrass while still producing significant amount of energy.

On the other side, nutrients are strongly limiting productivity in subsistence agriculture. According to SANCHEZ and SWAMINATHAN (2005), food insecurity in Sub Saharan Africa is first of all due to the low productivity of African soils and to the very limited nutrient inputs in smallholders' farms. Early estimations of nutrient balances in agro-ecosystems comparing nutrients inputs (addition of organic and mineral fertilizers, inputs from weathering, the atmosphere, and erosion) to nutrient losses (in agricultural products and through erosion, leaching, runoff, volatilization and denitrification) suggested that each year, each cultivated hectare in Sub-Saharan African was losing on average 22 kg N, 2.5 kg P and 15 kg K (SANCHEZ and SWAMINATHAN, 2005). These estimations were confirmed in Burkina Faso by LESSCHEN et al. (2007) with the use of a spatially explicit model including uncertainty estimations. DRECHSEL et al. (2001) observed a negative correlation between N balance and rural population density in Sub Saharan African countries and a positive relation between the percentage of arable land under fallow and the N balance. In their study, DRECHSEL et al. (2001) could not observe N balances higher than +10 kg N ha⁻¹ year⁻¹, but they calculated N balances as negative as -80 kg N ha⁻¹ year⁻¹. SANCHEZ (1998) suggested to replenish soil fertility in Africa by huge applications of local rock phosphate. However, according to FARDEAU and ZAPATA (2002) this strategy might not have the expected effects everywhere as rock phosphate can only release significant amount of P in acidic soils. The introduction of adapted plant germplasm with small amounts of fertilizers (so called "strategic inputs") as recommended in integrated approaches can increase plant productivity and restore soil functions (FROSSARD et al., 2007). For instance, in South America the introduction of *Brachiaria* grasses had a tremendous positive effect on pasture and animal production and on farmers' income (HOLMANN et al., 2003). In Africa, promiscuous soybean (*Glycine max*) in the humid areas and cowpea (*Vigna unguiculata*) in the dryer zones are getting adopted contribut-

ing to higher N input, food production and farm income (SANGINGA et al., 2003).

Animal production develops very rapidly in developing and transition countries in response to the increased demand of the population for meat and milk based products (DELGADO et al., 1999). On the one side, this “livestock revolution” bears the potential for improving food security and income for small holders, but on the other side this revolution might have extremely heavy environmental consequences. STEINFELD et al. (2006) cite effects on land degradation, atmosphere and climate, on water and on biodiversity. Overgrazing triggers pasture degradation and erosion, and expansion of cattle production leads to deforestation especially in Latin America where new surfaces are needed for pasture and feed crop production. Animal production is responsible for a very large proportion of CO₂, CH₄ and NH₃ emissions either directly through emissions from animals and from manures or indirectly through the production of crops that are used to feed animals. Livestock has also a strong effect on water either directly e.g. through wrong disposal of manures leading to degradation of superficial and groundwater quality or indirectly through the use of irrigation water for the production of feed crops.

Developing and transition countries, besides Brazil, want to cultivate large surfaces of crops for the production of agro-biofuels. This will have consequences for nutrient fluxes and soil fertility. Whereas it is recognized that the production of oil palm requires high N and K inputs, a lot of hope is also placed on plants like *Jatropha curcans* that can supposedly grow on degraded soils without irrigation and without fertilizer input. This would give the opportunity of growing energy plants on soils which could not be used for food production. But to be productive all plants need a minimum of nutrient and water. So although *Jatropha* would certainly have its place in specific agro-ecosystems, we think that before propagating its cultivation on a large scale much more information is required on the agronomic practices necessary to reach high sustainable yields (OPENSHAW, 2000).

6 Which are the research priorities related to nutrient use for future sustainable agricultural production systems?

In 2003–05 the FAO counted 848 million of chronically hungry people on earth; these are 6 million more than in 1990–92 which was the baseline for the world food summit.

The high food prices after 2006 caused an estimated increase of 75 million of hungry people. About 28 % of the hungry are in India, 25 % in Sub Sahara Africa, 14 % in China and 22 % in the rest of Asia and in the Pacific (COMMITTEE ON FOOD SECURITY, 2008). According to TILMAN et al. (2001), world agricultural production will have to be doubled in the next 50 years to cover the needs of 9 billion people. This increase will have to be much higher in areas where population growth is high and production is low. COLLOMB (1999) estimates that African countries will have to multiply the production of plant-derived energy for human consumption by a factor 5 and even by a factor 7 for those countries where staple food are root and tuber crops, whereas countries of Latin America and Asia will “only” have to double the production of plant-derived energy. These increases will have to be achieved mostly through increases in agricultural productivity with fewer natural resources.

In his report presented in 1995 in Lucerne to the Consultative Group on International Agriculture Research and published in 1997 CONWAY suggested moving from the “green revolution” to a “doubly green revolution” to meet this challenge. According to CONWAY (1997), this “doubly green revolution” should repeat the success of the green revolution in terms of productivity increase, it should occur on a global scale, and in addition to the “green revolution” it should address many diverse localities, be equitable, allow the development of resilient production systems (CONWAY uses here the term “sustainable”), and be environmentally friendly. For GRIFFON (2004), this “doubly green revolution” will have to increase agricultural productivity as much as possible by using the own capacities of ecosystems. For instance, nutrients should be used as efficiently as possible by implementing the integrated nutrient management schemes mentioned above. Techniques of soil conservation (e.g. no-till) should also be used as much as possible as they need less energy, allow erosion control and increase soil organic matter and biodiversity. Integrated water management must become reality, e.g. to improve irrigation techniques without triggering soil salinisation. The “doubly green revolution” requires crops that are tolerant to biotic and abiotic stresses and that are accepted by the consumers. It also requires the application of integrated pest management schemes e.g. using adequate crop rotation to limit the development of soil borne diseases, or taking advantage of naturally present parasitoids to control plant parasitic organisms. Altogether these approaches should allow the development of production systems that enable farmers to better resist environmental and economic stresses (e.g.

stresses resulting from climate change). All of this will need to be planned and implemented in collaboration with farmers and other stakeholders taking into account local knowledge. Some institutional and economic components of this “doubly green revolution” are given by GRIFFON and WEBER (1996). The “doubly green revolution” does not attempt to eliminate variability but makes use of it to increase and stabilize production towards regional optima determined by local economical, ecological and sociological constraints. The “doubly green revolution” is using and conserving the potential of production of a given area, i.e. conserving soil fertility and biodiversity allowing an increased local economical, ecological and sociological resilience. This “doubly green revolution” is very knowledge intensive and demands strong interdisciplinary, inter-sector and spatialized approaches. It should make full use of the new developments in ecological science and in biotechnology described above (CONWAY, 1997). The need for research in relation to nutrient cycling in agro-ecosystems to achieve this goal is given below.

At the process level, we assume that a lot can still be discovered in soil biology. Information on the functional diversity of microorganisms (fungi and bacteria) should help to better use nutrients (such as N and P) since microorganisms are both a source and a sink of nutrients (BÜNEMANN et al., 2007). This research must be based not only on molecular techniques to identify the organisms but also on physiological tools to evaluate their activities *in situ*. This research could lead to inoculation strategies and/or to the development of agricultural practices improving crop nutrition through managed microbial populations (TURNER et al., 2006; JANSÁ et al., 2006). We need to better understand how plants and their symbionts adapt to nutrient scarcity and other soil abiotic stresses to develop productive cultivars for low input systems (BRANCOURT-HUMMEL et al., 2003). The relations between nutrient management and plant health and the importance of the soil fauna on nutrient cycling and availability must also be better understood (ALTIERI, and NICHOLLS, 2003). Finally, “safe” recycling of wastes and by-products will become more and more important in the future. This will require more information e.g. on the speciation and availability of the elements in these by-products, but also on industrial processes allowing the separation of pollutants from nutrients while keeping these in a plant available form (ADAM et al., 2009; LIENERT and LARSEN, 2007).

At the system level (production system, watershed, landscape), research is needed to evaluate how the different

components (microorganisms, crops, animals, soils) should be best organized to optimize nutrient use efficiency and to minimize losses (OBERSON et al., 2006). For instance, before organic farming can be seen as a global solution to our problems, we must evaluate its long term effect on nutrient use efficiency (including nutrient mining and nutrient losses) compared to other integrated production systems where fertilizers (mineral and/or organic) are added so as to replace what has been exported (OBERSON and FROSSARD, 2005). Nutrient losses need to be further studied at the system level. We now realize that limiting a certain type of loss can lead to an increased loss somewhere else in the system. Therefore priorities have to be set to identify the losses which can be afforded. But setting priorities is strongly dependent of the system under study. Such approaches could lead to expert systems that will allow supplying the minimum amounts of nutrient at the right place and moment for optimum yields and minimum losses. Obviously, studies linking natural, engineering and social sciences are needed. Research should also be carried out on how to limit the negative impacts of livestock on the environment, e.g. by a proper integration of crop and livestock in areas where these are separated. Research is also needed to assess the long term consequences of energy crops on the soil ecosystem and on nutrient use. Besides field approaches which will remain extremely important, this research will require integrating modeling tools as described by FELLER et al. (2004) as well as participatory approaches taking into account the local knowledge to make sure that solutions are really implemented.

This challenge needs to be recognized at the societal level so that proper political decisions are taken to protect soils and to use nutrients as efficiently as possible. Besides regulating inputs and waste production, it will also be important to realistically price natural resources as soil, water, energy, phosphate and the use of waste disposal to improve the use efficiency of natural resources (STEINFELD et al., 2006).

7 Concluding remarks

The lessons learnt from the nutrient management practices discussed in this paper and their potential and limits are summarized in the Table 1.

In early times the scarce nutrients were used in a parsimonious way. The value of recycling was largely recognized. Nutrient deficiencies however were severely limiting crop

Table 1: Summary of the lessons learnt on nutrient management
 Tabelle 1: Zusammenfassung der Erkenntnisse in der Nährstoffbewirtschaftung

Origin of the nutrients applied to the cultivated field	Nutrient management option	Agricultural management option	Potential and limits
Nutrient inputs from outside of the region to the cultivated field	Input of water soluble fertilizers	Input of NO_3NH_4 , urea, triple super phosphate, KCl	Water soluble fertilizers increase nutrient availability to crops; Non-water soluble fertilizers have a variable effect; Excessive fertilizer inputs cause environmental problems; Fertilizers are produced with non-renewable resources.
	Input of fertilizers that are not water soluble	Input of rock phosphate, rock powder	
	Import of fodder on the farm	Fodder for animal production	Excessive nutrient input as fodder causes excessive manure production, which when applied causes environmental problems.
	Increase N_2 biological fixation	Legumes	Legumes need appropriate conditions to fix N_2 in large amounts.
Nutrient inputs from the region to the cultivated field	Nutrient scavenging	Animals roaming at large during the day and kept at night on cultivated fields, Shifting cultivation	Sustainable at low population level.
	Nutrient transfer between farms	Transfer of manure from one farm to the next	Limited by the cost of manure transport.
	Waste recycling	Input of sewage sludge, composts, ashes etc.	Limited by the pollutant load of the waste; Nutrient availability might be limited in certain wastes: "proper recycling" will become more important in the future.
Nutrient recycling from the farm to the cultivated field	Animal manure recycling	Integration of crop and animal production	Manure brings significant amounts of nutrients and organic matter; The fertilizer value of manure is very variable and difficult to estimate as it depends on many factors.
	Transfer of plant products	Planting of hedges Cut and carry of forage	Works well but ultimately limited by the input of nutrient from outside of the farm.
Nutrient recycling within a cultivated field	Solubilize insoluble nutrient (P, K, micronutrients)	Integrate in the rotation crops known to solubilise nutrients	Apart from a few species (white lupine, rapeseed), other plants have a limited access to non-soluble forms of nutrients; Research is needed to develop further "solubilising" crops; This option will not have a lasting effect in soils that have limited nutrient stocks.
	Lift nutrient from deeper horizons to the surface	Plant deep-rooting species (agroforestry/intercropping)	Agroforestry/intercropping systems are not simple to establish (competition between plants, growth length ...).
	Rotation	Choose adequate crops in rotation (e.g. cereal following legume)	Works well but ultimately limited by the input of nutrient from outside of the farm.
Improved use of already available nutrient within a cultivated field	Provide soil conditions allowing optimum nutrient acquisition	Drainage Soil amendments Superficial soil preparation	Works well but ultimately limited by the input of nutrient from outside of the farm.
	Limit nutrient losses from the field	Erosion control Fertilizer application techniques Match nutrient application to plant needs	
	Use cultivars with high nutrient efficiency	Select plants that provide high yield at low nutrient availability and/or tolerant to abiotic stresses	Some crops are known and used but research remains to be done to identify and develop further nutrient efficient crops.
	Multicropping/mixed cropping	Plant species or cultivar mixtures	Must be studied on a case by case basis, some associations show transgressive overyielding while other show yield decrease.
	Manage soil micro and macrofauna	Select appropriate crops, rotation, fertilizing strategy and inoculants	Management of soil biota in situ is a challenge! Inoculation in agricultural systems has only been successful for rhizobia.
May include several or all the above described origins	Implement integrated nutrient management schemes	May include several or all the above described options	Must be participative, taking into account the traditional and local knowledge as well as the science-derived knowledge and must encompass a broad range of scales in space and time.

production and therefore agricultural development. The needs of the future generations were *de facto* respected, but the needs of the populations present at the time were not fulfilled.

Since the theoretical basis in plant nutrition and soil science has been established and since large deposits of P, K, S and energy are being exploited, very large quantities of nutrients are currently available. These are largely used in intensive agriculture. The needs of specific parts of the population are now fulfilled without thinking about the needs of future generations. The bad news is that a large fraction of the world population that is living from subsistence agriculture remains untouched by this increase in agricultural production. The situation is still deteriorating for this often poor and undernourished population.

Although we are still in a time of plenty in industrialized countries, we see that it will not last forever. The development of integrated approaches, including integrated nutrient management schemes, within a “doubly green revolution” can help to sustainably cover the needs of future generations. But to achieve this more research is needed. Thereafter we must hope that these concepts will become implemented on a large scale.

Finally, this paper shows how the focus in soil science changed with time. Till the end of the XIXth century the soil was mostly studied as a support for plant growth. Most soil scientists were actually agronomists or foresters. They had set the conceptual basis of plant nutrition. At this time very few scientists, as FALLOU (1862), MÜLLER (1889) and DOKUCHAEV (1883), were studying the soil for itself and therefore little was known on nutrient dynamics in soils. Then, during the XXth century the soil was mostly studied for itself. Soil scientists interested in nutrients studied the internal cycle of nutrients in the soil. Now the soil scientist interested in nutrient cycling has become a “pedo-bio-geochemist”. He/she does not study any more only the internal nutrient cycles in soil, but contributes to the study of global nutrient cycles with colleagues from other disciplines.

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