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Definition of sustainable and unsustainable issues in nutrient management of modern agriculture

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Abstract. Sustainable management of nutrients in agricultural systems is critical for sufficient production of nutritious foods and to minimize environmental pollution. In this overview, we discuss some of the most important factors influencing nutrient cycling, and how practices for sustainable nutrient management can be optimized. In most cases, problems are associated with excessive use of nutrients (manures, other organic amendments, and inorganic fertilizers). Options for dealing with such problems at the farm level include: reducing nutrient inputs to balance exports, increasing the land area on which manures are applied, and export of excess nutrients from the farm in the form of value-added products. These strategies can be used singly, or in combination. Nutrients in the human food chain are often not recycled back to primary crop production. To manage such issues, and avoid regional nutrient accumulations, we need to develop a better understanding of large-scale nutrient flows, and develop policies to manage them. We stress the importance of scale when considering nutrient management in the future.

Keywords: Agricultural emissions, farming systems, nutrient management, nutrient budgets, sustainable agriculture

DEFINITION OF SUSTAINABLE AGRICULTURE

The question of ‘what is expected’ from sustainable agricultural systems, in terms of the use of plant nutrients, is relatively easy to answer. We want to produce healthy and plentiful food, with minimal negative impacts on the environment. However, despite the fact that considerable research with this focus has been conducted in recent years, it has proved difficult to attain these goals with practical management measures. In fact, potential negative effects of agricultural production on natural ecosystems and the quality of food products have been topics of worldwide concern for several decades. Such adverse effects include deterioration of surface and groundwaters by plant nutrients (Roberts & Marsh 1987; Burt *et al.* 1988), including drinking water quality, accumulation of agrochemicals in soil to toxic levels (Torstensson & Stenstrom 1990), and redistribution of eroded material (Walling 1987; Lal 1990). In many countries, market-driven forces in agriculture have frequently overshadowed considerations of environmental protection, unless there is progressive regulatory support.

As a result of the increasing concern over food and environmental quality, completely new agricultural concepts have been developed, commonly classified as 'sustainable agriculture'. Sustainable agriculture, which is a goal rather than a distinct set of practices, was defined by Benbrook (1991) as a system of food and fibre production that: (i) improves the productivity of soil, water and other natural resources and cropping systems so that farmers can meet increasing levels of demand in agreement with population and economic growth; (ii) produces food that is safe, wholesome and nutritious, thereby promoting human health; (iii) ensures an adequate net farm income to support an acceptable standard of living for farmers; (iv) complies with community standards and meets social expectations.

In other words, in developing the concept of sustainable nutrient management, it is fundamental to consider not only the productivity/economic aspects of crop and livestock production, but also environmental and societal impacts associated with these activities, and to strike a reasonable balance among these three key factors.

In this paper, we provide an overview of the factors influencing nutrient cycling at different scales, which serves as an introduction to other papers included in this Supplement to *Soil Use and Management* and presents some ideas for optimizing practices for sustainable nutrient management. Sustainability concepts will be discussed, including both physical and biological components, as well as some socioeconomic aspects of importance for nutrient management.

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SUSTAINABLE PRODUCTION CONCEPTS

Conceptually, one can position a farming system within a virtual 3-D cube, the three axes of which are represented by *'productivity/economics', 'environment'* and *'societal impacts'.* The spatial position of a farm within this cube will be determined by the balance between the three variables, which are largely a consequence of government (municipal to federal) policies and on-farm management choices. While decisions regarding both economic and environmental issues are usually science-based, societal issues tend to be more perception-based, and often more difficult to anticipate and manage from the farmer's perspective.

In Figure 1, two hypothetical farms, F1 and F2, are depicted. Farm F1 is operated to achieve near-maximum levels of productivity (yield), at the expense of environmental issues, and with less regard for societal issues. In comparison, farm F2 somewhat reduces the level of intensity of its practices, and may sacrifice a little financially by responding to both environmental and societal issues. Thus within the virtual cube, the position of F2 is more towards the centre than F1, which is closer to the economic axis. Although the financial return from F2 will be somewhat less than that of farm F1, its input costs may also be less, so that the net difference may not be so great, when both environmental and societal benefits are factored in.

An example of the F1 type of farm might be an intensive livestock operation with insufficient land for applying manure, and with little regard for optimizing methods for storing, handling and applying manure. As a consequence, there are likely to be excess nutrient accumulations on the farmland, which increases risks of surface and/or groundwater contamination by nutrients or pathogens, and also of excessive odours in and around the farm buildings, and in the vicinity during manure application. Even though there may be no actual health or safety issues associated with the farming operation, nearby neighbours will dislike the odours from the operation, and may perceive that the farm interferes with the safety of their environment. If ignored, societal issues can quickly become political in nature, overriding any science-based decisions and resulting in the farmer losing control over the situation.

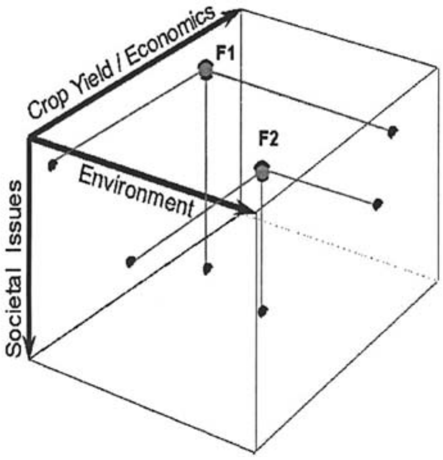

Figure 1. Sustainable nutrient management-balancing economics, environment and societal issues. Comparison of two differently managed farms (F1, F2).

IMPORTANT ISSUES IN THE DEVELOPMENT OF SUSTAINABLE CROPPING SYSTEMS

Even though the overall goals and ideas of sustainable agricultural systems are clearly defined, the various forms can range considerably in scope. On the one hand, we find very low-input systems with the goal of achieving sustainability by incorporating biologically based practices that result in complete independence from purchased inorganic fertilizers and agrochemicals. On the other hand, many conventional agricultural practices can, with care, be fully sustainable and will continue to play important roles in agricultural systems of the future. Indeed, conventional systems may in fact be more sustainable than some forms of low-input cropping systems, due to difficulties in managing nutrient balances and controlling leaching losses (Kirchmann & Bergström 2001), as discussed below.

Temperate agriculture

In temperate regions, which are the focus of this Supplement, current cropping systems and their spatial distribution are ultimately determined by climate. This has led to large regional differences in cropping and in crop production practices. For example, in Sweden, sugar beet is only grown in the south of the country, cereal crops dominate around the big lakes in central Sweden, and in the north perennial forage crops play a central role in rotations. These cropping systems are also a reflection of the type of animal production in the different regions, for example forage crops are naturally grown in areas where milk and livestock production are important.

However, unlike forage crops, grain for pigs and/or poultry is commonly transported great distances from its original site of production. In Sweden, pig and poultry production are concentrated in the south, whereas, as mentioned above, cereal crops are commonly grown in central Sweden. A contributing factor to this development, in the era following World War II, was that the relatively cheap and plentiful supply of inorganic fertilizer N replaced a significant fraction of livestock manures as the primary nutrient source for crop production in the industrialized world. This facilitated the decoupling of traditional crop production from livestock production, as larger, more efficient cash crop operations flourished, relying on only synthetic fertilizers.

Similarly, it became more profitable to increase the intensity of livestock production units, which increasingly lacked sufficient land area for effective utilization of the nutrients in the manures they produced, while at the same time increasing the use of imported, rather than on-farm, feed inputs. In parts of North America, the consolidation of the livestock meat packing industry further promoted intensification and localization of livestock operations in regions surrounding those facilities.

An important consequence of the dislocation between crop and livestock production has been the development of regional nutrient accumulations from poultry and livestock production that are not recycled back to source for the next crop production cycle, while the crop producing areas relying on inorganic fertilizers lack the important soil quality enhancements that livestock manures offer. It is well known that soil organic matter not only enhances nutrient storage and water holding capacity, but also improves soil structure and aeration necessary for optimum crop growth. Severe nutrient imbalances may occur both on a regional scale as well as at a farm level. In the large cereal growing areas without animal production, other negative long-term effects may also develop, such as: greater dependence on synthetic pesticides, soil compaction, and depletion of biological diversity. Similar problems may also develop on farms with pig/poultry production, resulting potentially in large leaching and runoff losses of nitrogen (N) and phosphorous (P), and volatilization losses of ammonia. A somewhat different situation prevails in areas where milk/livestock production dominates, due to the large proportion of perennial crops in such systems. For example, in Sweden, less nitrate is leached from perennial forage crops than from annual arable crops (Bergstrom 1987), whereas P losses may increase due to applications of large quantities of manure.

Phosphate deposits

Since phosphate fertilizers are mined from natural deposits which are finite in supply, P should be considered a non-renewable resource that must be effectively recycled through the production system. Unfortunately, some natural deposits of phosphate (apatite in Idaho, USA) contain relatively high concentrations of some heavy metals, such as cadmium, lead and arsenic, and thus their use for crop production should be curtailed. Additional problems for phosphate fertilizer production include negative impacts on the water table during the mining process and fluoride byproducts, which have human health implications.

Management of nutrient excesses

As indicated above, the intensification of both livestock and crop production, has resulted in increased amounts and concentrations of excess nutrients in both surface and groundwaters at numerous locations throughout the industrialized world. A major source of nutrient accumulation has also occurred in the human food chain, where large-scale nutrient flows through the food processing industry and human consumption are not recycled back to primary crop production, but rather are stranded in landfills, or leaked into surface water through inefficient sewage processing systems (urban and rural). The key to managing these issues will be the development of better understanding of large-scale nutrient flows and of how to minimize regional nutrient accumulations.

Recent studies in the USA on whole-farm nutrient balances (budgets) have demonstrated that a large proportion of the farms studied have substantial nutrient excesses (input/output > 1.5), especially for N (Koelsch & Lesoing 1999; Cogger *et al.* 1999; Nord & Lanyon 2003). There are three options for dealing with on-farm nutrient excesses, which can be used singly or in combination:

- Reduce nutrient inputs to balance nutrient exports from the land area (e.g. improved feeding strategies including increased nutrient utilization).
- Increase the land area for manure application (buy/rent more land, or contract with neighbouring farms to receive excess manure); exporting liquid manure is usually limited by economics to an area within 15 km from the farm.
- Export excess nutrients from the farm in the form of value-added products. This requires three conditions: the products must be odour-free, pathogen-free and dewatered — essentially meaning that the entire manure volume must be processed, either by composting or by anaerobic digestion.

Farmers will need increased flexibility in managing nutrient budgets and on-farm nutrient excesses, as more stringent nutrient management and water protection legislation is implemented in various jurisdictions.

It has been calculated that: 'In the 20th century, human interference in the nitrogen cycle has caused a doubling of the global nitrogen fixation rate, thereby intensifying global nitrous oxide (N_2O) production during microbial nitrification and denitrification' (Barton & Atwater 2002). Consequently, it will become increasingly difficult to achieve or maintain current water quality standards for nutrients unless we curtail the large annual injection of inorganic fertilizers into the environment. Ways must be found to facilitate the large-scale recycling of nutrients (livestock and human food chain) to partially replace the annual tonnage of fertilizers in crop production. At the farm-scale or watershed scale, the use of nutrient accounting (whole farm nutrient budgets) will become an important environmental tool in this process.

Lift Cycle Assessment

Life Cycle Assessment (LCA) is another environmental management tool for evaluating the comprehensive environmental impacts of products, processes and activities, and will be instrumental in developing and optimizing more sustainable practices of nutrient management. LCA will identify 'environmental hot-spots' in the life cycle of target products (e.g. fertilizers, manure nutrients) from raw material sources through to end-use activities, taking into account such factors as air and water impacts, and efficiency in the use of energy (Cowell 1999; Sandars *et al.* 2003).

NUTRIENT FLOWS AT DIFFERENT SCALES

In most cases, agricultural emissions to the environment occur at relatively low rates over large areas, and can therefore be classified as non-point source or diffuse pollution. In addition to diffuse pollution of N and P, agricultural production is responsible for other transfers of nutrients, which are of importance to environmental quality.

In an attempt to classify key environmental concerns originating in agricultural production, Carton & Jarvis (2001) evaluated different environmental issues related to nutrients in terms of their impact, scale of agricultural contribution, on-farm sources and scale of impact. They showed, for example, that nitrate affects both water quality and the finances of individual farmers, and that agriculture is a major source of nitrate impacts through losses from intensively managed land. The scale of impact ranges from local to national/international: through contamination of individual groundwater wells to eutrophication of maritime waters. Agriculture is also considered as a major source of nitrous oxide and ammonia emissions resulting from inorganic fertilizer and manure applications, which contribute to global warming and acidification of soils, respectively. Ammonia has impacts, both at local and national/international scales, whereas nitrous oxide has mainly a global impact. These examples show that the scaling issue is of great importance when dealing with nutrient management and nutrient flows both within farms and at larger scales.

While the basic farm production unit is the most appropriate scale at which to manage nutrients, monitoring and assessment of nutrient management impacts are more appropriately evaluated at the small catchment scale. It is notable that a disturbance in the environment, for example eutrophication caused by elevated P loadings, is initially observed at catchment scale. In most cases, the problem is subsequently investigated in the laboratory or in small field plots, whereas implementation of proposed counter measures is carried out at field level. For further discussion of scaling issues see Shirmohammadi *et al.* (2005).

NUTRIENT FLOWS AND MANAGEMENT IN DIFFERENT TYPES OF FARMING SYSTEM

Farming systems with animals can range from low-input meat production, based entirely on grazing, to 'industrial' animal production in what are often referred to as CAFOs (concentrated animal feeding operations) or ILOs (intensive livestock operations). Between these two extremes are mixed crop and livestock farms, which derive income from both these sectors. In addition, a large number of farms are completely arable; in fact, arable farming is currently the largest agricultural land use in Europe (Eurostat 2000), as well as predominating in moisture-limited regions of the mid-western USA and Canada, where there is frequently insufficient water for livestock production. Nutrient management related to these farming systems is discussed in various papers included in this Supplement, and only a brief summary will be presented here.

The main difference between systems with and without animals is undoubtedly the production of manures. Several papers in this supplement emphasize the potential problems associated with the use of organic manures, such as increased emissions of nutrients to the environment, especially N. Organic N in manures applied to land continues to mineralize outside the cropping season, leading to increased risk of N leaching. In general, it is more difficult to predict nutrient availability from organic sources than from inorganic sources, because it involves biological processes that are highly dependent upon temperature and moisture.

The general opinion is that intensifying animal production increases the risk of environmental problems (Sims *et al.* 2005). However, we have to recognize that some techniques which improve nutrient-use efficiency are only viable on larger units producing larger amounts of manure. For example, anaerobic digestion of manures transforms up to 50% of the total organic carbon in raw manures into a valuable byproduct, namely biogas (methane ~ 60-65%, carbon dioxide ~35%), leaving a more highly mineralized, N-rich liquid fertilizer which can be applied to crops, in the same way as commercial fertilizers. Another example, which is also facilitated by large quantities of manure, is the possible use of ultra-microfiltration to recover the organically bound nutrients in inorganic form (Cicek 2003), followed by concentration (Kirchmann *et al.* 2005). The product of this process could then be used as an inorganic fertilizer and transported long distances to arable farms.

As animal manures are rarely used on arable farms, most environmental problems related to N in such systems are due to excessive use of inorganic fertilizers (Bergström & Brink 1986; Lord & Mitchell 1998), although research has demonstrated that fertilizer use at the economic optimum can also result in substantial amounts of nitrate leaching (Goulding 2000). Fallowing, being a common, politically-driven practice within European Union countries today, can also cause large N leaching loads, due to net mineralization of N and no crop N uptake (Wallgren & Linden 1991).

The problem of lack of synchrony between N release and need for N by crops is not only applicable to animal manures but also to other organic amendments, such as green manures (Bergström & Kirchmann 2004), which are sometimes used on arable farms. In a study over six years by G. Torstensson (pers. comm.) on a sandy soil in southern Sweden, a green manure input of 71 kg N ha^{-1} yr^{-1} resulted in an average N off take of 24 kg N ha^{-1} yr^{-1} in harvested crops and 39 kg N ha^{-1} yr^{-1} lost by leaching. When the green manure was replaced by inorganic N fertilizer applied at 97 kg N ha^{-1} yr^{-1}, the average annual crop off take of N was 77 kg ha^{-1} and 49 kg ha^{-} was lost by leaching. Adding a catch crop to the rotation with N fertilizer resulted in even smaller leaching loads (25 kg N ha^{-1} yr^{-1}) and more crop N off take (86 kg N ha^{-1} yr^{-1}). In other words, if we simply compare the leaching percentage of total N removal (leaching plus crop off take of N, excluding gaseous losses) in these systems, it was considerably larger when green manure was used in the crop rotation.

Even though most of the focus related to nutrient management and environmental pollution has been on N during recent years, other nutrients also need attention. Phosphates, besides being potential contaminants causing eutrophication in fresh water bodies, are a limited resource (Djodjic *et al.* 2005); both N and P have to be considered in sustainable management of agricultural systems. Potassium is neither a major source of contamination of natural waters nor a limited resource. However, under certain conditions, lack of sufficient K for crops can be a problem. For example, in organic farming systems where soluble inorganic K fertilizers are not used, growing potatoes on sandy soils can be a major problem. A high-yielding potato crop grown in northern Europe needs at least 200 kg K ha^{-1} to produce 40 t tubers ha^{-1} (Svanberg 1971), whereas the weathering capacity of a light-textured soil suitable for potatoes is commonly less than 5 kg K ha^{-1} yr^{-1} (Holmquist *a al.* 2003). Therefore, in organic farming systems without animals, lack of available K can substantially restrict growth of potatoes and some other crops.

In contrast, on intensive dairy farms where K inputs in imported feed exceed output in meat and milk products, repeated manure application to grass and alfalfa can result in luxury consumption of K. Excess levels of K in dairy cows can lead to reduced calcium absorption, which in turn can result in serious metabolic disorders such as milk fever, calving problems and displaced abomasums (Bittman *et al.* 1999). Potassium excess can also cause hypomagnesaemia in livestock.

In the study by G. Torstensson (pers. comm.) referred to earlier, the net P balance in the rotation with green manure was -6 kg P ha^{-1} yr^{-1} (no external P input and, on average, 6 kg P ha^{-1} yr^{-1} removed in harvested crops), whereas in the rotation that received fertilizer the balance was 7 kg P ha^{-1} yr^{-1} (an average input of 24 kg P ha^{-1} each year and 17 kg P ha^{-1} in harvested crops). Leaching of P was negligible in both cases. In terms of K, the net balances were negative in both rotations: -6 kg K ha^{-1} yr^{-1} with green manure only, and -5 kg K ha^{-1} yr^{-1} in the rotation with fertilizer but no green manure. However, 60 kg K ha^{-1} yr^{-1} on average was harvested in the latter case, whereas only 11 kg K ha^{-1} was harvested each year after green manure. In other words, if neither P or K fertilizers nor animal manures are used, there is an obvious risk of deficiencies developing. This is also true for essential micronutrients, although many soils have adequate weather-able reserves for the foreseeable future.

CONCLUSIONS

Balanced nutrient inputs and outputs are of the utmost importance towards attaining long-term sustainability in agricultural systems. The introduction of whole farm nutrient accounting is an important tool to direct the on-farm management of nutrients. We need to avoid depletion of essential nutrients as well as accumulation of toxic or polluting elements. When balance is achieved, we have a better chance to provide the crops with sufficient essential nutrients at the same time as avoiding large losses that can cause environmental disturbances. However, it is important to keep in mind that there is not one single solution for achieving sustainable farming systems with regard to nutrients. At farm level, nutrient management is controlled by government schemes as well as private initiatives. To avoid nutrient losses at larger scales, the spatial heterogeneity in the landscape has to be considered, so we use counter measures that are most suitable for each field or part of a field.

A rigorous effort needs to be made to increase large-scale nutrient recycling to reduce local/regional excesses of nutrients from livestock manures, as well as from those stranded in the human food chain. These recycled nutrients can effectively replace part of the large quantity of fertilizers applied for crop production, and help stabilize or reduce the overall levels of nutrients being introduced into the environment. Life Cycle Assessment will become another useful tool to identify and minimize ‘environmental hotspots’ in the patterns of use of fertilizers and livestock nutrients, and will provide a sound basis for developing policies that move agriculture a step closer to environmental and economic sustainability.

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