Anticipation study

NPK - will there be enough plant nutrients to feed a world of 9 billions?

Part III: Research and innovation aspects

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1 Introduction

It is expected that the world population will increase up to more than 9 billion people in the next 50 years. Therefore global supply of food, feed stuff, fibre and biofuel especially from land based production systems has to be increased significantly while, at the same time, agriculture's environmental footprint must shrink dramatically (Foley et al. 2011). According to Reynolds et al. (2009) the major challenges are to enhance crop yields and to stabilize plant development under less predictable growing conditions. However, for crop production finite resources (e.g. land, fossil water, fossil energy, and minerals) are consumed and non-agro-ecosystems are contaminated with multiple effects on environmental quality (Correll 1998, Erisman 2009, Schröder et al. 2011). Based on detailed calculations forecasting that the global demand for crop calories might increase by 100 % from 2005 to 2050, Tilman et al. (2011) conclude that environmental impacts depend on the strategy ("N minimizing" vs. "current N intensity" vs. "land sparing") how to cover this demand (Fig. 1).

Seen from a world wide perspective very few soils are sufficiently fertile to enable crops to exploit their yield potential without addition of plant available nutrients (e.g. Dawson and Hilton 2011), i.e. output from crop production relays to a large scale on adequate nutrient supply to the plant. On the other hand it has to be emphasized that the increased use of mineral fertilizers has somehow disrupted the delicate balance between localized production of food/feed/fibre/fuel at a level just sufficient for the people in a certain region and population growth resulting in constantly increasing demand for more agricultural products (Brown 2003).

Most important for plant productivity are the 3 so-called "macro elements" nitrogen (N), phosphorous (P) and potassium (K). Nevertheless, many other element (e.g. magnesium [Mg], sulphur [S], calcium [Ca] and micro nutrients like boron [B], copper [Cu], iron [Fe], manganese [Mn], molybdenum [Mo], zinc [Zn]) are essential for plants and need to be available in adequate amounts, otherwise plant growth (and as a consequence yield and/or quality) will be reduced (Dawson and Hilton 2011).

Important options to ensure that crop production will keep up with the global demand are the use of new farming technologies and the cultivation of more marginal land. In addition land use intensity has to be increased. This might imply the use of new high yielding varieties as well as higher inputs of plant nutrients and/or plant protections agents. However, there is great societal pressure that intensification of plant production should not lead to damage of non-agro-ecosystems. Although the debate is ongoing there is clear evidence that the overall ecological footprint per unit produce in intensive farming systems is not per se higher compared to that of low-input farming systems (Corré et al. 2003, Neeteson 2011). In the context of nutrient input it is therefore essential that nutrient use efficiency at plant and field level is improved. As a consequence consumption of plant nutrients (especially for N and P) can be reduced without jeopardizing the demanding production targets. This will reduce the pressure on the limited N/P/K resources and expand the time frame for usage.

In the framework of this report no special focus is given to aspects of **plant physiology** including the processes of acquisition, allocation and utilization of plant nutrients inside plants. Without no doubt there is ongoing need to further clarify all relevant biochemical processes down to the molecular level (e.g. selectivity of membrane transporters, signalling functions of nutrients). Based on many examples it has been demonstrated that membrane transporters are a key control point for nutrient uptake and use in plants, but still strategies to make use of these results for enhanced nutrient efficiency remain without success in many instances (von Wiren 2011). Further there is a clear need to initiate systematic measurements of nutrient related traits, physiological relevant processes in plant metabolism as well as interactions between soil nutrient content and root functioning. This kind of knowledge will contribute to enhance the exploitation of nutrient reserves in soil and/or contribute to improve nutrient use efficiency. Finally **breeding** (incl. all aspects of modern techniques associated with genetically engineering) of new varieties of already widespread used crop species or modifying species that have not been used intensively for crop production have a high potential to improve the overall nutrient use efficiency in the entire agricultural value chain up to the ultimate usage by humans. Also the controversial debate concerning a potentially establishment of N fixing bacteria at roots of non-legume plants (e.g. cereals) via genetic engineering, which would at least have a big impact on the nitrogen supply for crops, is not further explored.

Depending on the specific soil-plant-environment context the impact of micro-organisms (either as free-living species in the soil or in close vicinity to roots in the rhizosphere or symbiotic in nodules or within the plant) on nutrient supply for the plant might be quite significant. According to Smil (1999) and Erisman et al. (2008) half of the global food production currently can be related to naturally fixed nitrogen via bacteria. Also the soil internal turnover of organically bound nutrients is mediated by microorganisms. A considerable amount of details concerning the effect of plant growth-promoting bacteria on nutrient status of plants is available (see reviews by Lugtenberg and Kamilova 2009, Vessey 2003) and since many years various so-called bio-fertilizers are commercially available. Furthermore the effects of mycorrhizal fungi on the uptake of nutrients (especially phosphorus) by plants are highly relevant (Bolan 1991, Pringle et al. 2009). Although this study disregards these aspects this does not imply that these aspects are of minor importance when discussing nutrient use efficiency.

The present report tries to elaborate on research and development needs mainly with a focus on aspects related to N/P/K use at farm/field level. Although most of the literature used as a basis to describe the current situation including problems and risks as well as some of the knowledge gaps is originating from R&D work done in developed countries in the northern hemisphere, the principles can be translated to and adopted in other regions (e.g. less intensively managed farming systems in eastern European countries or subsistence/urban agricultural in sub-Saharan Africa; see e.g. Buerkert et al. 2001). Many of these aspects are discussed exemplarily using one specific nutrient. However, it has to be emphasized that for optimal plant development all so-called "growth factors" like light, water, nutrients, etc. need to be taken into account.

When screening the literature in the context of this work it became clearly evident, that (although potassium is one of the 3 "macro nutrients") neither mineral potassium stocks are under extreme pressure nor has the environmental burden relating to K use in crop production gained particular attention in the public debate. Otherwise agricultural use of nitrogen and phosphorous have been and currently are focal aspects when discussing about the "negative impacts" of agriculture. For these two nutrients this can be related to the problem of finite resource availability (fossil oil/gas for the ammonia synthesis; phosphate rock reserves/resources; for further details see Dawson and Hilton 2011, Schröder et al. 2011) and the adverse ecological effects due to N/P losses from agro-ecosystems (e.g. nitrate leaching, gaseous ammonia and nitrous oxide losses, P losses via leaching/runoff or wind/water erosion).

The following topics have been found relevant concerning future research and innovation needs:

- nutrient recycling at field/farm/regional level,

- application of N/P/K at field level,
- uptake from soil into plant/efficient use.

Although many aspects of nutrient use efficiency are discussed somehow separately, there is an evident need to support research work that is based on a system approach integrating the effect of different factors that determine plant performance (light, water, nutrients, pests, etc.) within different spheres (soil, phytosphere, atmosphere) at different scales (e.g. rhizosphere, bulk soil, sub-field zone, field, farm, agro-ecosystem, region).

2 Nutrient use in crop production: focussing on critical issues

2.1 Recycling of N/P/K for use in crop production

Introduction of "new" nutrients into crop production (N via bacterial or technical N fixation; P and K due to mining) can be seen as a very important driver for the world wide yield increase during the last decades. While arable farming systems mainly rely on these nutrient imports, mixed farms or specialized livestock farms need to take into account nutrients coming into the farm system via purchased feed stuff and which thereafter are applied as residues from animal production on crop land (e.g. farmyard manure, slurry). Furthermore N/P/K which have been exported as agriculture produce for usage in other sectors might be re-imported (e.g. composts, sewage sludge).

2.1.1 Farm internal nutrient streams

Calculation of nutrient import via feed staff (and other farm inputs like seeds, piglets/calves/chicks/etc) and nutrient export via products sold to the market is rather straight forward because huge datasets exist summarizing the nutrient concentrations of the various materials and products. On the other side it is quite complicated to get reliable facts on the nutrient concentrations of the organic residues from animal production. The efficiency of nutrient uptake from the feedstuff into the body of the animal (or produces like eggs, milk) is quite variable and as a consequence the nutrient concentrations in the excreta might vary also drastically. Furthermore the technical set-up of the husbandry system (e.g. construction of the stable, storage facilities for the excreta) has a significant influence on the nutrient concentrations. Inflows of rainwater into the storage system or gaseous N losses as ammonia are two examples that might lead to very different N/P/K concentrations. Furthermore a stratification of the nutrients in the storage tank for liquid manures might occur, which makes it inevitable that the farmer needs to carefully mix the slurry in the tank before application.

Calculations based on statistical data for Germany revealed that in 2008/09 about 69 % for P and 86 % K of the total nutrient usage were applied via organic manures (Albert 2010; Tab. 1). However, the correct use of such farm based organic residues in crop production depends heavily on the data available for the farmer in the moment when the application takes place. The problem with lab based analysis of the N/P/K concentrations is the time span (normally at least several days) between sample shipment and receiving the results. A rather recent progress in slurry testing is the so-called “IPUS Nanobag® Analyse” for slurries and biogas residues. This procedure uses for sample preparation/analysis a powdery absorption material based on nano-silicate for shipment of the slurry sample to the lab followed by routine near-infrared spectroscopy (Tauber et al. 2007). The most important benefits are a very fast response time (normally less than 5 days) and the relative exhaustive analytical report (e.g. dry matter, pH, total N, ammonia N, phosphate, potassium, calcium, magnesium).

Several quick tests for on-farm analysis of N (especially ammonia N as the directly available N form in organic fertilizers) are also available. So farmers can at least calculate the N application rate using data on ammonia N concentration (e.g. Chescheir et al. 1985, Piccinini and Bortone 1991, Van Kessel et al. 1999). The reliability of such quick tests is quite good: using the “Quantofix” meter a very close relationship to the lab results for ammonia has been proven in several studies (Klasse and Werner 1987, Van Kessel and Reeves 2000).

For optimal usage of farm based organic fertilizers for crop production it is essential to develop innovative analytical tools for N/P/K measurement (preferable robust on-site instruments). Even if these kinds of instruments are too expensive for individual farmers a rental service in partnership with local cooperatives or retailers will enable access. Data on N/P/K concentrations in organic fertilizers will allow the farmer to readjust the quantities of applied nutrients to the actual crop demand which will improve nutrient use efficiency and reduce the need for N/P/K import from external sources.

Furthermore research activities should be directed to elucidate the effectiveness of different nutrient binding forms. Plant availability of K in organic fertilizers is quite comparable to inorganic K containing salts as K is existent predominantly in the liquid phase. Nitrogen turnover and availability has been in the focus of many research projects during the last 3 decades and at least rather robust indications concerning practical farming conditions are available. However, knowledge about the P containing compounds is of special importance for the estimation of organic P availability as the turnover in the soil is depending on many factors (e.g. microbial activity, soil moisture and temperature, binding form). At EU scale, the new LUCAS-Soil data collected by the JRC on 22,000 sampling sites and including N/P/K measurements will allow for pan-European studies of N/P/K turnover and dynamics.

2.1.2 Nutrient import via waste streams from farm external sources

Reuse of nutrients that once have been exported outside agricultural production systems is of growing interest due to dramatic intensified urbanization in the last couple of decades. Huge amounts of essential nutrients (especially N/P) accumulate in sewage water from the food processing industry and of course in urban wastewater treatment systems (e.g. Richards and Dawson 2008, Rosemarin et al. 2010), but their usage in European agriculture is rather limited (Fig. 2). The installation of multistage biological and/or chemical wastewater treatment resulted in drastic reduction of N/P concentrations in the effluents discharged into surface waters in many European countries. The main driver for this development has been the ambiguous goal to decrease nutrient input into aquatic ecosystems to reduce eutrophication and associated negative impacts on fauna and flora (see also FFH Directive). In addition more and more composted materials based on (at least partly) organic matter from non-agronomic sources are available for application on arable land.

On the other hand these residues from wastewater treatments contain significant amounts of N/P/K that should be utilized in crop production. Unfortunately resistance to accept these nutrient sources in crop production is rather pronounced. For phosphorous Cordell et al. (2009) estimated that globally only 10 % of human excreta are recycled to arable soil. The major concern against application on farmland is the high risk of soil contamination due to significant concentrations with heavy metals and organic pollutants (e.g. PCBs, PAC, hormones, antibiotics) in many of these waste stream products. A strict quality control system implemented during the last years has led to a significant reduction of the contaminant level. However, the acceptance by land owners and farmers is still rather limited, resulting in quite significant amounts of nutrients which need to be treated via incineration or which are directly discharged to landfills.

A further problem with these kinds of materials is the uncertain effectiveness of the contained nutrients for plant growth. Addition of iron and/or aluminium salts is a widespread measure during chemical wastewater treatment. Phosphorous will be precipitated as Fe/Al phosphate and solubility under typical soil conditions is rather limited and quite often plants suffer from P deficiency although reasonable amounts of P have been applied via sewage sludge. Furthermore reactive Fe/Al salts added to the soil might even lower the P concentration in the soil solution impairing P uptake for plants compared to the situation before the sewage sludge has been applied.

Numerous R&D projects have been conducted since the late sixties/early seventies until nowadays to develop techniques for wastewater purification and subsequent treatment of the remaining sludge to remove unwanted components (see review by Sartorius et al. 2011). Although some new techniques have been implemented (at least in a pilot scale context) a continued development effort seems to be highly required. According to Horn and Sartorius (2009) P recovery from sewage water will become economical interesting at a price of ca. 100 US$ per tone rock phosphate. Innovative procedures developed for sewage sludge treatment might also be applicable for treatment of on-farm organic residues as problems with high concentrations of heavy metals (especially Cu/Zn) and residues from the use of veterinary medicaments are relevant.

2.2 Nutrient application

2.2.1 Fertilizer recommendation systems

In principle fertilizing strategies should always aim at maximising nutrient use efficiency, whilst minimising the use of limited resources (Neeteson 2011). Due to highly diverse growing conditions (i.e. different soils, weather conditions, crop rotations, etc.) nutrient requirements for the actually grown crop differs. Therefore farmers have to adopt the decision on fertilizer application rates/timing and on the right nutrient forms (e.g. mineral versus organic fertilizer, salts versus chelates) as a matter of principle every year on each field (e.g.

Olfs 2009, Schröder et al. 2000). Most fertilizer recommendations systems worldwide are based on either soil or plant sampling followed by lab analysis.

Lab based plant analysis is more or less internationally standardized. After drying, grinding and homogenization the organic fraction in the sampled plant material is digested so that the elements can be dissolved for the final determination. Depending on the final analytical method employed additional chemicals are added to this digestion solutions (e.g. for using photometric methods) or a direct measurement of the analyte is possible (e.g. flame photometry, ICP techniques). Following these procedures the total concentration of a nutritional element within the plant biomass (or defined plant parts [root biomass, above ground biomass] or plant organs [leaves of a certain age, stem, fruit]) is determined. Alternatively analytical procedures can be used that focus on specific (chemical) components (e.g. nitrate in the plant sap) to make a conclusion on the nutritional status of the plant and finally to decide on the need for nutrient application.

During the last decades more and more plant analysis tools for use at field level have been developed to complement lab based methods. The most prominent ones are so-called chlorophyll testers (e.g. SPAD, CCM100), that can be used by farmers directly at the field level to measure the greenness of plant leaves as an indicator for the chlorophyll content (see review Olfs et al. 2005). Due to the close relationship that has been proven for many plants between chlorophyll content and N status an indirect indication for N fertilizer demand can be derived. Just recently multi-parameter testers for use at field level have been developed that might be capable to widen the understanding on the nutritional status of plants including the manifold interactions of nutrients with the plant’s physiological processes (Lejealle et al. 2010). The most recent steps forward in this area are on-the-go plant sensors (for more details see 2.2.4).

Soil analysis as a basis for fertilizer recommendation has already been used at the end of the 19th century when agricultural advisors based on the ideas developed by Liebig in Germany, Lawes and Gilbert in the UK, and many others around Europe started to recommend farmers how much of a certain fertilizer product should be applied to a crop to achieve high yields. Comparing results from field experiments and analytical data on total soil contents of the three major nutrients N/P/K it became rapidly obvious that soil nutrients have to be differentiated into various "availability" fractions or pools (e.g. soil solution, "adsorbed", "fixed").

Numerous procedures have been (and still are) developed in different countries around the world to quantify the amount of soil nutrients available for the next crop or crop rotation and based on these facts deduce an appropriate fertilizer recommendation (Neeteson 2011, Olfs 2009). Somehow the diversity in soil analytical methods is reasonable, because soils used for crop production are quite different (e.g. soil parent material, humus content, pH). However, the debate why different methods to asses the plant available content of nutrients in soil result in rather divergent recommendation is still ongoing (e.g. Neyroud and Lischer 2003). Rather recently portable spectroscopy techniques have been tested and seem to be very promising tools for on-site N/P/K monitoring in agricultural soils.

During the last 2 decades there is a clear trend for harmonization of soil analytical procedures at international level driven by the European Commission thru its European Soil Data Centre at the JRC and soil labs offering cross-border analytical services. This kind of standardization is also driven by new analytical instrumentations offering multi-element analysis (e.g. ICP-OES [inductively coupled optical emission spectroscopy], ICP-MS [inductively coupled optical mass spectroscopy], XRF [X-ray fluorescence)]). These analytical procedures allow a much higher operational throughput, which will lead to lower costs for the farmer and/or to more detailed results for an individual soil sample. Furthermore consistency in using soil test methods across countries will alleviate the development of data based decision support systems because more farmers/advisors can make use of such a compatible multi-national software based system. A new high-resolution (90m) soil data base and map, based on digital soil mapping techniques, as currently developed by the GlobalSoilMap.net consortium, would be a very valuable base for farmers to take decisions on N/P/K application in the future (Sanchez et al. 2009).

However, the most important aspect in using any soil analysis data for fertilizer recommendations is a reliable calibration based on local multisite-multiyear field trials. As already mentioned for plant analytical approaches development of tools to measure soil nutrient status at field level (or even to get data on in-field variability; see 2.2.4) is a clear trend during the last couple of years.

Assisting farmers to adjust fertilizer application rates to the actual demand of the crop stand in each phase of the ongoing vegetation period is one of the most critical aspects for improved use efficiency for N/P/K. For obtaining nitrogen fertilizer recommendations field testing procedures (e.g. nitrate analysis of the stem sap using test strips in combination with low cost reflectometers) and several hand-held devices for chlorophyll measurement have been developed and introduced into farming practice during the last three decades (see above; Olfs 2009). This has led to improved N fertilization strategies with a much more targeted N application adjusted to the site and year-specific yield achievable. As a consequence oversupply (and undersupply) of nitrogen occurs less frequently.

There is a clear need to develop analogous tools for P and K which can be used by farmers on their fields, but currently no reliable P or K quick tests are available. Farmers either can try to look for nutrient specific changes at the plant leaves (e.g. older leaves with blue violet colour is typical for severe P deficiency, while K deficiency is visible as chlorotic and necrotic changes at the leaf tip/edge) or they have to take plant samples to be analysed for total P/K concentrations in a lab.

It must to be stressed, that not only new test kits for P/K need to be developed, but that this - as a matter of principle - needs to be done for all essential nutrients. Based on Liebig’s “law of the limiting nutrient” is has to be stated that there is a clear need to provide plants with all nutrients in a balanced proportion, as a deficit in any one could limit the crop’s performance leading to an unsatisfying utilization (in this case) of P or K. One fairly recent example is the manganese tester NN-Easy 55 developed at Copenhagen University, Denmark (Husted et al. 2009), enabling farmers and/or advisors directly in the field to precisely determine if the Mn status of the plant is adequate.

When looking at fertilizer recommendation activities in a broader sense there is a need to set up integrated decision support systems. In addition to the “one measurement – one decision” step for an individual farmer to decide on the next fertilizer application the measured data should be transferred into a software based recommendation system at regional scale. Developing data mining software for interpretation of this kind of on-farm collected plant nutrition facts and elaborate recommendations for farmers working under comparable conditions (e.g. soil, weather, crop rotation) will clearly improve farming practice at regional scale leading to more efficient use of plant nutrients.

In the same context development of crop growth models suitable for farm application should get high priority. Although forecast for rainfall, temperature and irradiation as the most (beside nutrient availability) important drivers for crop growth is still rather limited to a few days, retrospective modelling of the growth conditions for the crop could be seen as an interesting source of information, as it could help to calculate below and above ground biomass development (e.g. rooting depth/intensity, leaf area) and the amount of nutrients already taken up. Based on these numbers it can be judged if the N/P/K concentration in the plant tissue might be critical and if the plant's access to nutrients in the soil is sufficient.

2.2.2 Nutrient placement techniques

Placement of nutrients is a crucial issue in nutrient management because subsequent availability of nutrients for plants is strongly influenced (e.g. Scott et al. 1987). Unsuitable placement can reduce yield and result in economic losses for the farmer. Furthermore improper application of nutrients might lead to higher losses, which (in case of N and P) will most probably damage non-agro-ecosystems.

Decisions on nutrient placement must take into consideration soil characteristics (including all aspects of nutrient mobility in the soil), tillage practices (e.g. ploughing versus minimum tillage), crop choice and rotation aspects (e.g. rooting system), type of fertilizer being applied, application time in the growth period (e.g. pre sowing/planting versus at sowing/planting versus after sowing/planting) and finally of course access to adequate equipment. Consolidating these numerous combinations the following placement techniques are most relevant for practical farming: broadcast, surface band, subsurface band, point injection, seed coating. This categorization is based on the idea to concentrate the applied nutrients in a smaller soil compartment, thereby reducing unwanted reactions with soil components and thereby (hopefully) increasing nutrient use efficiency. Fertigation (see 2.2.3) and foliar application of nutrients somehow need to be distinguished from these techniques and discussed separately.

Broadcasting of fertilizers either before sowing/planting or during the season is the standard procedure for most broadacre crops (e.g. cereals, oilseeds) and obviously there is rather limited demand for extensive R&D initiatives. Ongoing activities in this subject are focussed on evenness of applied fertilizer particles on the soil surface (see 2.2.4) and on losses from applied fertilizers (especially gaseous losses via N_2O and NH_3; initiated due to climate change debates). Many (if not nearly all) aspects concerning N/P/K availability related to processes after the application of the fertilizer to the field at the soil surface, during infiltration into the soil following rainfall and reactions within the soil (e.g. adsorption at binding sites, chemical precipitation) have been investigate under various soil/weather/cropping conditions at field, greenhouse and lab scale.

The main effect of banded fertilizer (either as surface or as subsurface band) is the drastic reduction of reactions between the applied nutrients and soil components. Injection of fertilizers into the soil at one point can be regarded as a more extreme modification of subsurface band application. Under most circumstances any of these application ways reduces the risk that the solubility of nutrients will be decreased and on average a higher plant uptake can be expected. Obviously the effected of banding/injecting P fertilizers is most pronounced, because of its low mobility in most soils. Especially for crops with a wide row spacing (e.g. maize, sugar beets, potatoes) placing of P close to the seed or planting rows is reasonable (e.g. Neeteson 2011). The positive effects of P placement have been demonstrated for mineral fertilizers as well as for organic manures (e.g. Schröder et al. 1997, Smit et al. 2010).

Certain aspects related to banding of N/P/K have not been explored in each and every detail so that some functional aspects still remain unrevealed. In most cases band applied fertilizer has a high attraction for roots. As a result root density around the band is higher. However, more in-depth knowledge is needed concerning the rooting pattern in the non-effected bulk soil and what might be the consequences for uptake of all other nutrients not offered in the band and if water supply for the plant is affected.

Seed coatings provide an opportunity to apply nutrients (and other materials like pesticides) very close to the seed so they can effectively influence the growth and development of each seedling. Such close placement of N/P/K may improve crop establishment because each seedling has direct access to nutrients (in addition to those nutrients inside the seed), giving it a competitive advantage during early seedling growth (e.g. Ajouri et al. 2004, Peltonen-Sainio et al. 2006, Rebafka et al. 1993, Ros et al. 2000). In the nineteen-seventies and nineteen-eighties quite some research was targeted to nutrient seed coating (e.g. Leikam et al. 1983, Scott et. al 1985, Scott et al. 1987, Smid und Bates 1971) with a main focus on adding P to the coating. When using these kind of nutrient containing coatings problems might occur with emergence of the seeds (Scott et al. 1987). Interestingly many patents have been filed on different techniques and materials appropriate for seed coating during the last three decades, but practical relevance in broadacre crop production is still rather limited. There might be some demand for revisiting aspects of nutrient coating (e.g. interaction of nutrients used for seed coating, combination with seed priming, critical concentrations for nutrient coatings). A special focus should be given to the elucidation of the mode of action and to clarify under which soil/weather/crop conditions a positive effect on N/P/K use efficiency can be expected.

2.2.3 Fertigation

Fertigation (here used in its narrow definition: application of fertilizers through an irrigation system) is used extensively in modern agriculture and horticulture especially in semi-arid and arid regions mainly in “stationary” crops (e.g. orchards, plantations) and vegetable crops. Knowhow requirements to manage fertigation systems are increasing because fresh water resources are becoming scare (Balendonck et al. 2010). Nowadays fertigation even is used in cold-wet climates in western and central Europe for high value crops (e.g. potatoes) or in distinct periods of the season with limited rainfall. One of the key benefits of fertigation over traditional broadcast application of fertilizer is the increased nutrient absorption by plants resulting in higher nutrient use efficiency. This can be explained by a multifactorial combination of effects: (1) nutrients are localized close to the plant (i.e. nutrient placement; see 2.2.2), (2) nutrients are already dissolved and can be transported directly with the irrigation water into the rooting zone, (3) leaching of nutrients to deeper soil layers is reduced because water application rates are adopted to the water holding capacity of the soil and (4) application of nutrients can be executed at the precise time of crop demand. Furthermore fertilizer application rates can be changed during the growing season in order to adjust for specific nutrients requirements during different developmental stages (e.g. root growth, flower/potato tuber initiation, grain filling). Relevant drawbacks are (1) high costs for the technical infrastructure and installation, (2) imperative use of high quality fertilizers with low content of impurities, and (3) availability of water in adequate quality. Applications of phosphorus (as well as nitrogen in the form anhydrous ammonia) are sometimes risky if the irrigation water contains calcium, magnesium, and hydrogencarbonate, because these nutrients might form precipitants and clog the irrigation system.

A core challenge to enable a broader usage of fertigation in typical arable crops (e.g. cereals, oil seed rape, corn, pulses) is to adapt the technical set-up keeping in mind that these crops are high acreage/low value crops. Annual soil tillage (even with reduced intensity), sowing/planting, application of fertilizers/pesticides and finally harvesting the crop make it necessary that the field is completely accessible by machinery, so that either a mobile or a sub-soil fertigation system might be adequate options for these kinds of arable crops. Although some adoptions are already tested under practical farming conditions (center pivot systems combined with dripperlines or drip tapes) there is clear need for additional research on fertigation techniques in arable crops. From a plant nutritional point of view in context of the three macro-nutrients again P should be given a clear priority. However, concerning the application of nitrogen via fertigation knowledge gaps exist on N losses via denitrification. Aspects that need attention in this context are the impact of different N forms (nitrate versus ammonia/urea) in the fertilizer used for fertigation (including the turnover in the soil and additives that will inhibit the formation of nitrate as the most important source of N_2O losses) and the interaction of water content in the soil zones directly effected by fertigation with the N content in the soil solution.

2.2.4 Precision nutrient management

The ideas around precision agriculture have been worked out mainly during the last three decades. Within this conceptual framework precision farming (PF) should be viewed as a system approach to crop production. Although PF started as a technology-driven development (e.g. yield mapping, variable rate technology) for identifying and managing spatial variability within a field, it can nowadays be defined as a management concept with the goal to reduce decision uncertainty based on better understanding to manage in-field variation at the spatial and temporal scales that are most relevant (for more details see Auernhammer 2001; Pierce & Nowak 1999). Expertise from many disciplines is utilized including information technology to integrate data from multiple sources and scales to enable decisions on how to manage crop production. Focus has been given to in-field variable soil tillage, seeding, application of pesticides and fertilizers as well as on yield mapping.

Within the context of this report it is assumed that other inputs (at this step of the process) are either non-limiting or already optimized to cover in-field heterogeneity. Precision nutrient management (PNM) can than be defined as a cluster of tools and techniques to adopt nutrient supply to the crop demand taking into account the in-field as well as the temporal variability.

PNM has to be seen as a cyclical process: (1) assessment of the extent and temporal dynamics of variation, (2) knowledge based interpretation of the data, (3) nutrient application at the appropriate scale and in a timely manner, and (4) monitoring the outcome to validate the decisions. Under practical farming conditions different approaches (mapping, real-time sensing, modelling) or combinations of these are in use. Finally these integrated activities should result in a more efficient use of nutrient. However, if farm profits will be higher due to PNM mainly depends on the variation at sub-field level, relevance of differential nutrient needs during the growing season and on the costs for the additional technical equipment/labour involved.

In the past PNM has focused much on variable rate application of N/P/K fertilizer (Pierce and Nowak 1999). One strategy was based on yield mapping as tool to calculate nutrient offtake from the soil and balance this export via differentiated N/P/K application before the next crop is grown. However, this implies that yield in each and every part of the field is not limited by one of these major nutrients. If availability of N, P or K for the crop is responsible for a yield decrease such a N/P/K balance strategy will even deteriorate the situation for the next crop. An alternative strategy is based on assessing spatial variation of the soil nutrient status (and/or other soil attributes that interact with nutrient availability, e.g. soil texture, pH; e.g. Olfs et al. 2010), followed by interpolation procedures to convert point based data into application maps (e.g. Franzen and Peck 1995) to calculate fertilizer needs accordingly. This is more or less a transformation of the conventional fertilizer recommendation schemes into a highly spatial resolution approach at in-field level and it is under debate whether this is a suitable strategy (Hergert et al. 1997).

Different sampling strategies (simple grid sampling, targeted sampling according to soil property maps) have been evaluated in many regions around the world. Dividing a field into few, larger sub-units (so-called “management zones”; Chang et al. 2003; Franzen et al. 2002; Ping and Dobermann 2003) that are thought to behave differently in terms of crop growth as a basis to guide soil sampling might be an option to reduce high sampling cost as those represent a major obstacle to farm profitability. In North America and Europe these kinds of PNM approaches are offered to farmers by commercial farm service companies.

More recently on-the-go soil sensing has gained more acceptances (Adamchuk et al. 2003, Dobermann et al. 2004, Olfs et al. 2005; Fig. 3). Available sensors and techniques have been tested and evaluated in extensive field trials across Europe within two large research projects of the European Commission: DIGISOIL and iSOIL. Full results are available at the EU Soil Portal (http://eusoils.jrc.ec.europa.eu/projects/Digisoil/). Different technical equipments are available for on-farm use to measure soil electrical conductivity, soil texture, soil water content, or soil organic matter content (e.g. Allen et al. 2007, Gebbers and Adamchuk 2010). However, most available soil sensors provide only indirect data on the soil status, e.g. soil electrical conductivity is used to differentiate soil texture, but it is also influenced by soil moisture, salinity and organic matter content (Corwin and Lesch 2003). Rapid measurement of soil nutrients during or before soil management might be done via optical diffuse reflectance sensors or via electrochemical sensing using ion-selective electrodes or ion-selective field effect transistors (Kim et al., 2009). Such kind of on-the-go vehicle-based sensing systems have potential for efficiently and rapidly characterizing variability of soil nutrients within a field (Sinfield et al. 2010), but results obtained so far for N and K appear not sufficient reliable as a basis for decisions on fertilizer rates to be applied. However, the increase in sampling resolution, cost digression and synergy with other management activities might lead to increased acceptance (Zaks and Kucharik 2011).

It is generally believed that PNM compared to uniform field management will result in economic and environmental benefits (e.g. Bongiovanni and Lowenberg-DeBoer 2000; Wang et al. 2003), but results from field studies are not consistent. However, using site-specific N management strategies reduction in N application rates for a field and/or yield increases have not always been found (Dobermann et al. 2004). It is also not yet clear whether PNM approaches will reduce the nitrate leaching risk (Ferguson et al. 2002). For nutrients such as P and K mixed results have been reported (e.g. Lowenberg-DeBoer and Aghib 1999; Pierce and Warncke 2000; Weisz et al. 2003). Variable rate application of P/K inputs usually increased soil test values in areas of a field with low content of plant available P/K and application of these nutrients could be reduced in high-testing areas, but such redistribution did not always increase crop yield or net returns (Swinton and Lowenberg-DeBoer 1998).

In-field variable N application strategies have been in focus of many R&D projects since the mid 1990´s in North America and Europe for several reasons (e.g. see review Olfs 2009). First of all nitrogen is the most important nutrient responsible for growth limitation, i.e. less than optimal N application will directly result in a considerable yield decrease, while discontinuing P/K fertilization for 1 (or even several seasons) might not lead to a visible yield impact for many soils with an adequate P/K nutrient reserve. On the other hand oversupply of N might often results in an increased demand for crop protection (e.g. fungicides, plant growth regulators) and a higher risk for N leaching and/or gaseous losses (ammonia volatilization, denitrifikation) with a negative impact on non-agricultural ecosystems.

While yield maps were found to be appropriate for assessing P/K replenishment levels in the course of a crop rotation, variable N application strategy needs to be optimised in each particular growing period using season-specific information and even multi-season yield mapping did not enable a reliable N fertilizer recommendation at sub-field scale for the actual growing season (Olfs et al. 2005). Therefore it was found necessary to use real-time data on the crop's nitrogen status at the growth stage when N fertilizer applications are relevant to optimise yield response. The most promising approaches to estimate the spatial variation in N status are remote sensing techniques like satellite imaging, digital air photography or tractor based spectral scanners.

Failure of PNM at field/farm level can be explained by several reasons including: (1) poor sampling strategies resulting in high costs while spatial variation is not adequately taken into consideration so that indigenous nutrient supply is insufficiently characterized, (2) calculating fertilizer recommendation based on prescription algorithms that are not appropriate for site-specific management, and (3) lack of nutrient management adjustments in-season to account for the actual growing conditions (Dobermann et al. 2004).

Specific sensors for assessing the soil status on crop available N/P/K are still not available for use for practical farmers. Development of such nutrient specific soil sensors should gain high priority in the context of PNM when focussing on spatial variability. Furthermore focus should be given to develop nutrient sensing tools to enable monitoring changes in nutrient availability through out the growing season.

Overall there is a need to develop more integrated forms of PNM. Such future solutions should focus on more flexible characterization of aspects that determine crop performance and input use efficiency. Under most circumstances a combination of historical data (e.g. multi-year yield maps, soil maps), real-time data acquisition techniques (e.g. soil/crop sensors) and short to medium term forecasts based on modelling (e.g. crop growth based on soil water availability and climate) seem especially promising. Extensive research activities on advanced digital soil mapping techniques are on-going within the JRC of the European Commission (http://eusoils.jrc.ec.europa.eu/projects/Dsm/).

Models are valuable tools to exploit complex data and can be used to simulate the relationship between environmental conditions and relevant factors influencing plant growth. Models might even replace field data when data collection is too costly, impractical or time consuming (e.g. Zak and Kucharik 2011). However, models need to be robust enough for on-farm decision making and the amount of required input data should be restricted to a minimum. Such models could be used either to test different nutrient management options before the start of the season (e.g. based on historical weather data and actual soil status) or in-season estimation of changes in actual crop biomass, predicting yield and finally nutrient uptake to adjust fertilizer rates (van Alphen and Stoorvogel 2000).

The two most prominent challenges are (1) to ensure that data acquisition, decision-making, and nutrient application have to be done in near real-time and at miniaturized scales, and (2) to create automatic procedures based on generic/mechanistic algorithms rather than relying on empirical interpretation.

A rather recent trend is the development of small autonomous field robots (e.g. Blackmore et al. 2007, Pedersen et al. 2006). First prototypes have been developed and tested at lab and field scale (e.g. Ruckelshausen et al. 2007). Based on highly precise geo-referenced navigation, equipped with a set of diverse operating measurement systems for soil and plant sensing (e.g. cameras, spectral imaging systems, light curtains, distance sensors) such a field robot platform can be used to do repeated measurements of the (nutrient) status for an individual plant within a field (Ruckelshausen et al. 2009, Weiss and Biber 2011). A wide range of plant parameters can be determined and used for decision making (Tab. 2). A major challenge for developing reliable autonomous robot systems is the complex and changing environment (e.g. temperature changes, light conditions, wind, dust) at field level. Future improvement activities for such autonomous scouting platforms should also be focused on the capability to interact remotely with other clones as well as with a central decision support system. Allocating intensive R&D efforts to this topic a “single plant management” concept seems to be a vision within reach at least for row crops like maize, sugar beets or potatoes.

During the last years PNM has been developed as a management concept to decrease decision uncertainty caused by spatial variation. It is nowadays in general accepted that managing temporal variation is as important. One of the most challenging tasks in PNM is to transform the collected bits of information into a meaningful decision at farm level (Kitchen 2008), so that nutrient use is most efficiently to fully explore the yield potential of a crop, minimize environmental risks and preserve limited resources.

2.3 Technical equipment for application

One of the key driving forces for the progression of precision farming was the option to use the Global Positioning System (GPS). This has created new opportunities for vehicle guidance in agriculture. In the context of fertilizer application probable benefits for crop production and the environment primarily arise due to more precise application, i.e. using GPS enables the accurate positioning of the fertiliser spreaders so that overlaps and skips on the headland and in wedges can be minimised. Even though vehicle guidance has been adopted by quite a lot of farmers in North America and Europe, its impacts on farm profitability is not documented well (Dobermann et al. 2004). Also the effects of such GPS guided fertilizer application on the uniformity of the nutrient spreading pattern still needs some more attention. Manufactures of fertilizer spreader equipment (e.g. Amazone, Rauch) have already worked on this topic to solve the technical details (variable speed of the discs, different contact points for the fertilizer granules on the discs, variable dosage and control by weighing cells). When starting at a new field first of all fertilizer is applied along the boundaries of that field so that the GPS data can be recorded. Than specialized software calculates the exact fertilizer rates for each section within the field and regulates fertilizer application via a control unit on the tractor. In conclusion it can be stated that adequate application technique to achieve a homogenous spreading pattern for mineral fertilizers is already available.

Application technique for organic fertilizers has also been improved during the last years. Many up-to-date slurry tankers are equipped with more sophisticated distributor systems (e.g. drag pipes, sliding shoes, or nozzle spreading distributors) to ensure an even application of the nutrients in the organic manures and to reduce ammonia losses into the atmosphere. Slurry injectors place the slurry into the soil which will further decrease the amount of N lost as gaseous ammonia and which in addition lead to a placement effect of the nutrients (see 2.2.2). It is obvious that further technological developments will be initiated by the equipment manufacturers driven by their ambition to offer innovative spreader equipment to outperform competitors in the relevant market segment. One rather small competence area which might need some further support for innovation is on-the-go sensing technique to analyse N/P/K concentrations in slurries during the application process and simultaneously cross-check to nutrient demand in that individual subunit of the field and adapted the slurry application rate accordingly. Prototypes of such slurry tankers have already been constructed based on NIRS technology (e.g. Scotford et al. 1998, Sorensen et al. 2007).

3 Priority areas for research and innovation

Application of N/P/K is one of the most important aspects in crop production to ensure adequate plant growth. The basic principles are rather simple:

- soil fertility status concerning content, buffering, availability, accessibility of nutrients for the plants need to be checked and adjusted,
- nutritional status of the crop (depending on nutrient uptake and use efficiency) during different periods of the growing season has to be traced/forecasted and nutrient supply accordingly modified,
- for sustainable production nutrient offtake by the harvested crop has to be replaced by adequate nutrient supply via fertilization.

The challenge for the farmer is to collect all relevant data in adequate resolution concerning space and time (note that data in this respect can mean any kind of information being soil/plant analytical results, historical data on crop rotation, yields, fertilization, actual weather data, sensing data, observations by eye, expert knowledge, farmer's experience, etc.), to process these very different bits of information and to make the right conclusions always against the background of a sometimes very fast changing environment. In addition the conflicting economical and ecological requirements have to be respected.

In the framework of this anticipation study on the challenges of N/P/K availability for crop production several aspects related to nutrient use at field/farm level have been highlighted. Based on brief descriptions of the actual situation critical points were discussed. For benchmarking the following criteria are used (see details in Tab. 3):

- impact on nutrient use efficiency,
- impact on N/P/K savings,
- barriers for adaptation,
- relevance for different intensity levels of production (high = intensive farming according to standards in developed countries; medium = transition/emerging countries; low = developing countries mainly with subsidence farming),

- relevance for small-sized/large-sized farms,
- need for public and/or private subsidised R&D programs,
- volume of required budgets.

Most of these classifications are not based on hard facts, but reflect somehow the opinion and statements that experts in the different knowledge areas have expressed in published papers. Without no doubt these assessment is provisional and needs adjustment based on further literature surveys and discussion with expert panels.

3.1 Innovation needs concerning N/P/K use from farm internal/external streams

The effect of optimal usage of nutrients in slurries and other organic material originating from the farm entity itself on N/P/K savings at field, farm, regional or national level is highly variable. As a rule of thumb it can be concluded that a simple input-output calculation at farm level gives quite a good estimation if a surplus or deficit of nutrients has to be expected. If the nutrient budget is balanced at farm level more detailed calculations should be done at field (and sub-field) level. Redistribution of organic manures from one area to another (taking also the soil nutrient status and the crop's N/P/K demand into account) must be the consequence to ensure optimal use efficiency. As soon as this balance at farm level is positive nutrient export becomes obligatory which should result in reduced need for "fresh minerals" for the farm (or region) receiving the organic residues. This principle is more or less accepted through out the farming communities in many countries. However, implementation at farm level is often inadequate.

The major barrier to adaptation is lack of knowledge on the nutrient content (or in other words: the economic value) of this kind of products due to nonexistent analytical tools for use at farm level. Financial support should be directed to develop tools for accurate determination of N/P/K in slurries (preferable for each batch of organic manure taken from storage).

A second major issue for research should be directed to further develop low cost high efficiency technical systems for separation of organic manures into different fractions or for upgrading (e.g. nutrient supplementation) so that mid or long distance transportation is reasonable. During the last decades many procedures have been tested and prototypes as well as pilot scale units are available, but use at farm level is rather limited. This might be due to quite high investment costs for such equipments which finally add to much extra costs. One way to solve this problem might be to construct mobile units for usage on many farms.

The conclusion on N/P/K originating from farm external sources (mainly from food processing industry and sewage works) is much more straightforward: each kilogram of nutrient re-used for crop production can substitute N/P/K from mineral (and organic) fertilizers. According to Rosemarin et al. (2010) the reuse rate of nutrients from such “wastes” is unfortunately rather low through out Europe ranging from around 70 % (e.g. France, UK) to 0 % (Greece, The Netherlands). There is a high reluctance to apply such products in crop production, because it is primarily seen as a pollutant. Innovative procedures for cleaning up these materials from heavy metals, organic pollutants, antibiotics and pathogens are most of all required to enable the sustainable use of such nutrients.

3.2 Innovation needs concerning nutrient application

Soil and plant analysis is the backbone of any fertilizer recommendation scheme. Historically such methods have been worked out independently within a certain agro-ecological region for each nutrient and calibrated against the results of multi-site/multi-year field experiments. Currently there is a trend for standardization of analytical procedures and for multi-element assays. Initiating engagement of multi-national groups at European level to further develop soil and plant based methods is highly desirable. This will support knowledge transfer within Europe and improve the cross-boarder utilisation of such methods.

In addition R&D activities should be supported to develop innovative analytical tools that enable measurement of soil and/or plant nutritional status by farmers in the field. Based on such data farmers can fine-tune the fertilizer rates to the actual demand of the crop avoiding under- or over-fertilization. This will not always result in N/P/K savings but it can be expected that the applied nutrients are more efficiently used. Most critical for successful introduction of such a data based fertilizer recommendation system is acceptance by advisors and farmers. This will need low cost, robust, easy to handle and reliable measuring tools and an adequate communication strategy.

Placing N/P/K into the soil will result in higher concentrations of nutrients in certain parts of the soil attracting roots (thereby increasing nutrient uptake) and furthermore this will reduce unwanted interactions of nutrients with soil components that might decrease plant availability of the applied nutrients. Generally this should result in reduced needs for N/P/K because the overall nutrient use efficiency is improved. Although nutrient placement is established practice (especially for row crops like maize) there is substantial demand for basic research to clarify the mode of action in-depth and to increase the knowledge of the manifold interactions under practical growing conditions to enable a substantial improvement in advising farmers when and how to use fertilizer placement techniques. This is of special importance in regions with intensive livestock farming so that the use of the organic manures at farm level can be improved.

Nutrient supply using fertigation systems can be seen as a very promising application strategy because nutrients are dissolved in the irrigation water, penetration of the nutrients into soil is usually unproblematic and so uptake efficiency is high. Furthermore application of nutrients via fertigation also takes advantage of placement benefits (see above). Overall this results in N/P/K savings per unit area compared to broadcast fertilizer. However, willingness of farmers to install fertigation systems for arable cops is rather limited due to high investment costs, extra workload for installing the fertigation system and difficulties during crop management when fertigation lines are placed on the soil surface. Financial support to develop sub-soil permanent fertigation equipment or adequate mobile fertigation units easy to use in broadacre crops is highly reasonable.

All aspects mentioned above will of course lead to a more precise nutrient supply. While these activities are targeting a field (or at least larger subareas of a field) as one unit, precision nutrient management (PNM) can be seen as a conceptual approach to optimize nutrient supply for the crop taking into account spatial and temporal variability based on as much information as relevant for the decision (Gebbers and Adamchuk 2010). This will evidently either result in higher yields at a certain N/P/K amount applied per field or lead to lower N/P/K application rates necessary due to higher nutrient use efficiency. The size of this savings depends on the quality of nutrient input at the initial (pre PNM) conditions, i.e. the more advanced the fertilizer regime has been the lesser reductions in N/P/K use might be.

There are many opportunities to improve the data flow between sensors, models, and end-user inputs, but data are rarely useful by themselves. Not until integration into decision support systems is done value is added to the decision-making process due to providing timely, relevant information to the hands of decision makers (Zak and Kucharik 2011). The final intention must be to develop PNM based on a holistic approach. Important elements of this PNM concept will be remote sensing monitoring systems with real-time, internet-connected sensor webs (Adamchuk et al. 2004, Rundel et al. 2009,) including data mining software applications in combination with modelling of soil/plant processes to transform raw data into useful information for the decision-making process (e.g. McLaren et al. 2009). Obviously good educated farmers (in many cases managing larger-sized farm unit) will anticipate these developments much earlier and will adopt their farming practice accordingly.

Keeping this multi-factorial situation for crop production in mind, prioritizing needs for research and innovation is therefore rather inadequate. Depending on the situational context (soil <-> crop <-> developmental stage <-> external factors) the impact of one or the other "improvement in N/P/K use efficiency due to R&D" might be very different. However, the dominating element for optimization in this complex interactive set-up is knowledge based decision support.

4 Concluding remarks

Land based production of food/feed/fibre/fuel for a growing population with increasing needs (and in addition for more refined/superior meat and dairy products) is depending very much on adequate availability of nutrients for plant growth. Without nutrient input via fertilizers (either mineral or organic sources) production will sooner or later be negatively effected. Most important under current agro-ecological conditions in many regions world wide are nitrogen and phosphorous, while for potassium (and other essential nutrients) the situation concerning magnitude of reserves/resources and environmental risks are not so critical. On the supply side finiteness of resources (fossil oil/gas, phosphate rock) has to be taken into account. Focussing on P this requires an ambitious reduction in the use of freshly mined rock-based P fertilizer and a much improved recycling and reuse of P from waste streams for crop production.

However, to reach the final target of resource oriented N/P/K input in agricultural production the widespread use of empirical rules and algorithms concerning the application of nutrients must be replaced with more in-depth understanding of the cause-effect relationships. Although research and development focus areas within the framework of this anticipation study are mainly derived from knowledge gaps identified for N/P/K use in intensive agricultural systems in Western Europe the outcome of such innovation initiatives will also be beneficial for medium intensive farming systems in regions like Eastern Europe and low intensive/subsidence crop production systems in regions like sub-Saharan Africa. It is self-evident that the improvement of a system that is far below optimum needs a gradual approach starting with the most limiting factors but having in mind that an intelligent combination of moderately increased nutrient inputs adapted to the actual nutrient demand and applied in a way to insure efficient uptake by crops will lead to disproportionately positive effect.

At first glance high costs for and unavailability of many products/services seem to hold back more efficient use of N/P/K as a basis for optimum crop production, protection of neighbouring ecosystems and adequate consumption of finite resources in developing countries. Nevertheless, this is more a question of how to adjust the measure to the actual situation. Even certain precision framing procedures might be transferable to a subsidence farm household: at the end of the day it is about spatial and temporal available information on soils and crops to reduce the uncertainty of the decision to be taken. Because the traditional way of crop production in these regions is often not based on and stimulated by science and research the need for information/knowledge actually might be even greater in developing countries.

There is no single solution towards a sustainable nutrient use in crop production. In addition to strive for increased nutrient use efficiency, minimizing losses from agro-ecosystems as well as recovering and re-using N/P/K from all relevant “waste streams” are of major importance to enable nutrient input for a long-term productive agronomy. This can only be achieved in a strategic framework integrating all relevant stakeholders in the whole value chain from “mine to fork” and having in mind that the decision on how to optimize N/P/K use depends very much on the specific crop production context. Furthermore designing sustainable agricultural systems for food/feed/fibre/fuel production will need to consider other global challenges including environmental (e.g. climate change) as well as social aspects (e.g. urbanisation).

Figures and Tables

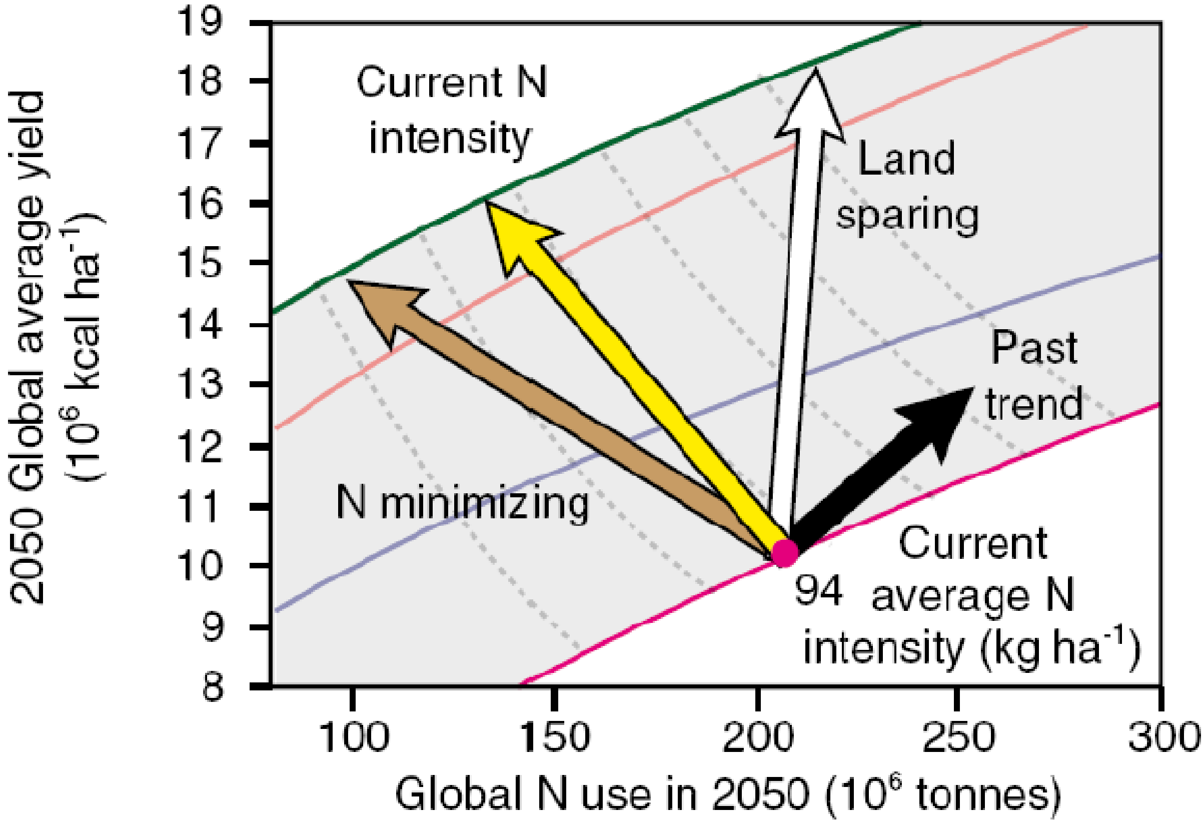


Figure 1: Impact of four alternative trajectories along which agriculture might develop by 2050 (Tilman et al. 2011)

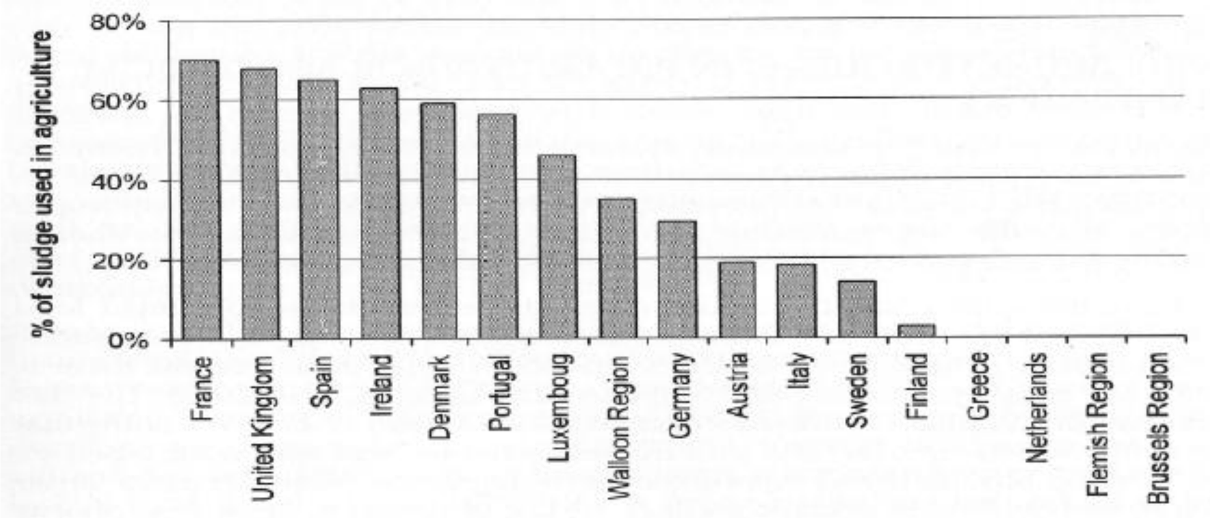


Figure 2: Proortion of sludge reused in agriculture in 2005-2007 ((Rosemarin et al. 2010)

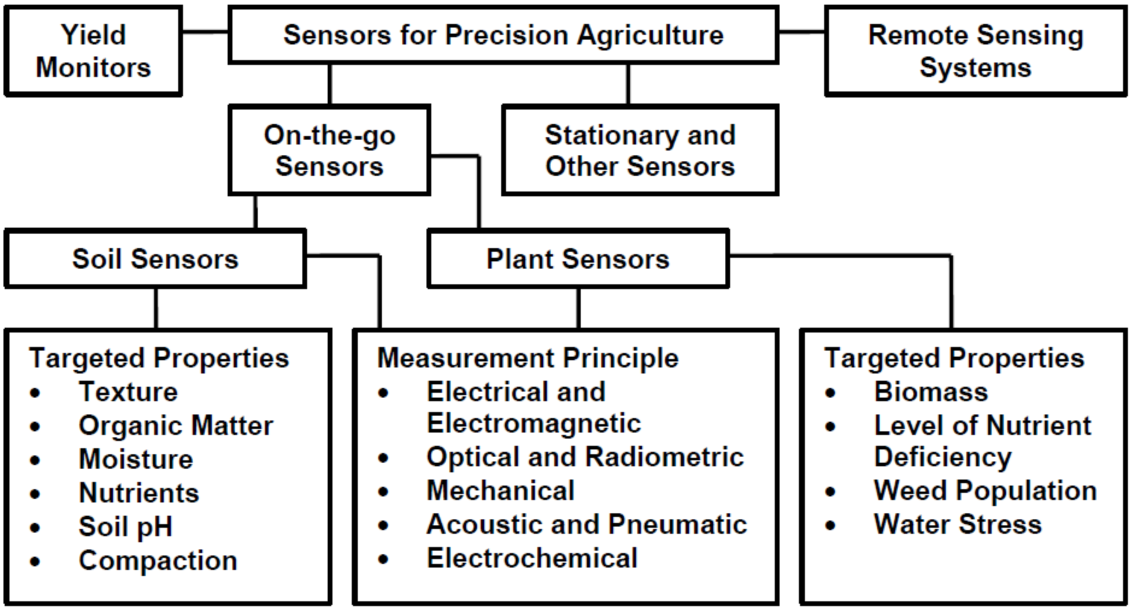
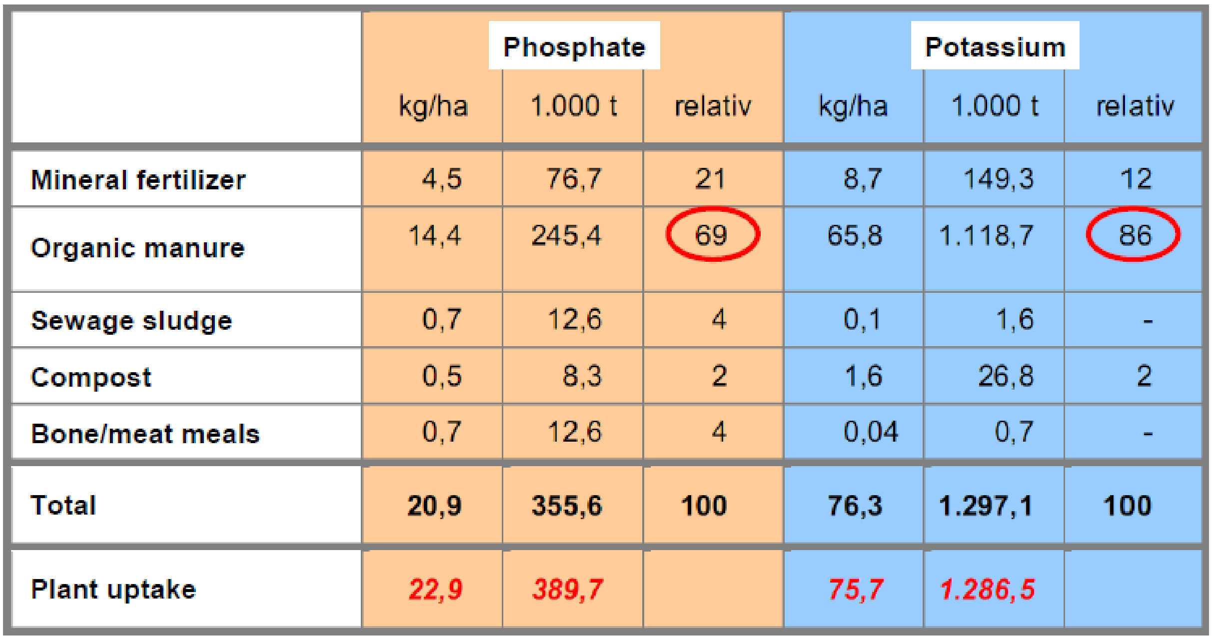


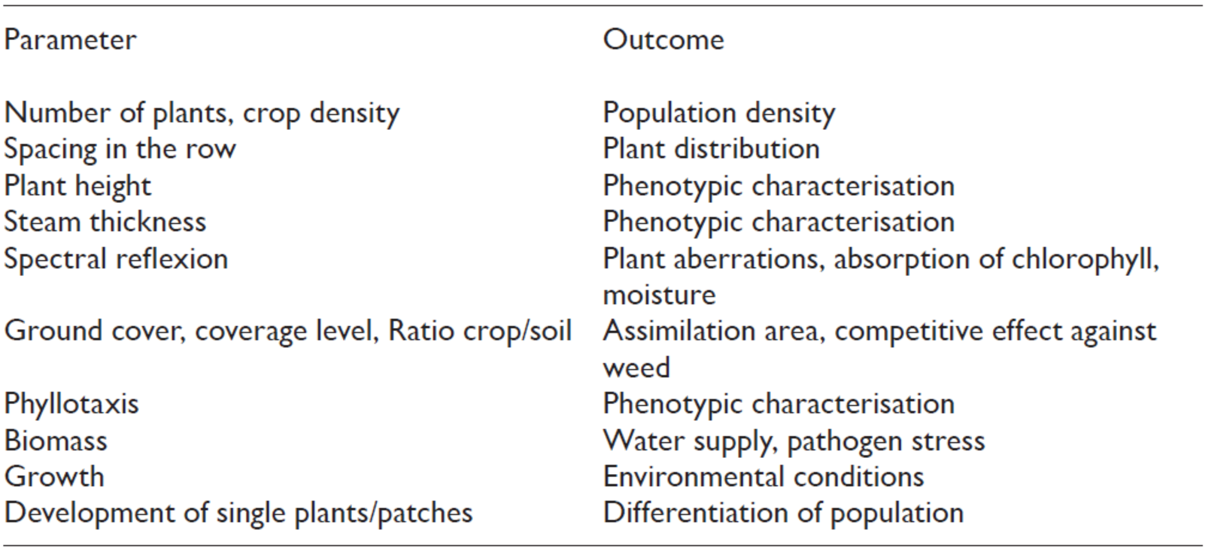
Figure 3: On-the-go soil and plant sensors used in precision agriculture (Dobermann et al. 2004)

Tab. 1: Nutrient content, total amounts and relative contribution of different fertilizer categories (adopted from Albert, 2010)



	Phosphate			Potassium		
	kg/ha	1.000 t	relativ	kg/ha	1.000 t	relativ
Mineral fertilizer	4,5	76,7	21	8,7	149,3	12
Organic manure	14,4	245,4	69	65,8	1.118,7	86
Sewage sludge	0,7	12,6	4	0,1	1,6	-
Compost	0,5	8,3	2	1,6	26,8	2
Bone/meat meals	0,7	12,6	4	0,04	0,7	-
Total	**20,9**	**355,6**	**100**	**76,3**	**1.297,1**	**100**
Plant uptake	***22,9***	***389,7***		***75,7***	***1.286,5***	

Tab. 2: Plant parameters assessable using the autonomous field robot platform BoniRob (Ruckelshausen et al. 2009)



Parameter	Outcome
Number of plants, crop density	Population density
Spacing in the row	Plant distribution
Plant height	Phenotypic characterisation
Steam thickness	Phenotypic characterisation
Spectral reflexion	Plant aberrations, absorption of chlorophyll, moisture
Ground cover, coverage level, Ratio crop/soil	Assimilation area, competitive effect against weed
Phyllotaxis	Phenotypic characterisation
Biomass	Water supply, pathogen stress
Growth	Environmental conditions
Development of single plants/patches	Differentiation of population

Tab. 3: Classification Matrix

	Impact on efficiency	Impact on savings	Barriers for adaptation	Relevance for			Relevanz for		Need for		Involved budgets
				high	medium	low	small-sized	large-sized	public	private	
				intensive production			farms		R&D		
Plant Physiology	+++	+	low	+++	+++	+++	+++	+++	X		high
Breeding/GMO	+++	+	low/high	+++	+++	+++	+++	+++	X	X	high
Microorganism											
N fixing bacteria	0	+++	low	+	++	+++	++	+++	X		medium
myccorhiza	+++	0	low	+	++	+++	++	+++	X		medium
Recycling of nutrients											
farm internal nutrients	++	++	low	+++	++	+	+	++	X		low
nutrient distribution	++	++	low	+++	++	+	+	+++	X		low
analytical tools	++	++	low	+++	++	+	++	++	X	X	medium
nutrient binding form	+++	+	low	++	++	++	++	++	X		low
recovery techniques	+	+++	medium	+++	++	+	+	+++	X	X	medium
external sources	+	+++	high	+	++	+++	++	++	X		medium
quality/nutrient binding form	+++	+	high	++	++	++	++	++	X		low
recovery techniques	+	+++	low	+++	++	+	++	++	X	X	medium
Nutrient application											
Recommendation systems	+++	++	low	+++	++	+	+	+++	X		medium
on-farm soil/plant testers	+++	++	low	+++	++	+	+	+++	X	X	high
decision support service	+++	++	low	+++	++	+	+	+++	X		high
Nutrient placement	+++	++	low	+++	++	++	++	++	X		low
Fertigation	+++	+	medium	+++	++	+	+++	+	X		low
Precision Nutrient Management	+++	++	low	+++	++	+	+++	+++	X		medium
on-the-go soil/plant sensors	+++	+	low	+++	++	+	+	+++	X	X	medium
permanent in-season sensors	+++	++	low	+++	++	+	++	+++	X	X	medium
soil/crop modelling	+++	+	medium	++	++	++	++	++	X		medium
holistic decision support systems	+++	++	medium	+++	++	+	++	+++	X		high
autonomous sensing robots	+++	0	high	++	0	0	+	+++	X	X	high
Technical equipment											
for mineral fertilizers	+	+	low	+++	++	+	+	++		X	low
for organic fertilizers	++	++	low	++	+	0	+	++		X	low

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