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ENPOS Energy Positive Farm

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Upkeeping the production capacity of agricultural land

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Introduction

Soil quality (or land quality in broader term) is the ability of a soil (land) to perform **functions** that are essential to people and the environment. Soil quality can be defined also in more simple way – how well soil does what we want it to do. Taking account the slow rate of soil formation, soil is considered as a limited and **non-renewable resource** on a 50–100 year timescale. Soil is not only the basis for food, feed, fibre and fuel, but also provides services beyond productivity function. Soil forms the spatial dimension the building of houses and infrastructures, recreation facilities and waste disposal. It provides raw materials, including water, minerals and construction materials. It forms an essential part of the landscape, conserves the remains of our past and is itself a relevant part of our cultural heritage. Soil is also central regulator of ecosystems quality through filtering, buffering and transformation capacity between the atmosphere, hydrosphere and biosphere. Soil functions are performed on different spatio-temporal levels and are determined by inherent soil characteristics (texture, organic matter, pH, cation exchange capacity, porosity etc.) and external environmental (climate, terrain, hydrological, biological) and anthropogenic (soil-use and management) factors. Crop yield can be used as an integrator of the soil indicators.

The most important in agriculture is biomass production (productivity) function of soils. This function is directly related to **soil fertility** which is measure of the ability of soil to provide plants with sufficient amount of nutrients and water, and a suitable medium for root development to assure proper plant growth. In addition to the natural soil fertility plant growth can be increased by investments such as from fertilizer, soil tillage, drainage or irrigation etc. Soil fertility is one component of land productivity that is strongly influenced by management. Production capacity of agricultural land and its actual realization is sum up of natural soil fertility, climatic conditions, human-regulated soil/crop management practices which are determined by the various technological and socio-economic factors.

Sustainable agriculture is aimed to preserve or improve production capacity of land in the balance with ecologic and socio-economic goals. Risk of soil degradation can derive from natural processes (erosion, landslides, acidification, paludification etc). Those forms of degradation are often intensified by human interactions, e.g. by different forms of land use. Therefore, human activities are regarded as the main causes of soil degradation risk.

Nowadays, increasing attention is given to sustainable and effective use of natural resources. Alternative agricultural systems, which can ensure an ecologically cleaner and healthier environment, have gained significantly more importance (Kirchmann and Ryan 2004). The applied agricultural system determines the efficiency of use of resources (including energy), the nutrient balance of soils as well as the general state of the environment and agro-ecosystems. Energy analysis of farming systems is raised in the focus of sustainable land use.

Energy analysis in agriculture is commonly the calculation of various criteria (energy gain, energy ratio etc) based on inputs and outputs. In plant production highest energy ratio is often achieved in low input farming systems. However, in low-input farming without adequate compensation plant biomass is largely formed at the expense of soil resources. In long-term this can lead to deterioration of the land productivity. Unless intending to endanger the soil fertility nutrients and soil organic matter must be replaced at a rate at least equivalent to their removal. Also other investments like regular maintenance of drainage systems are especially in Nordic conditions crucial to keep land productivity. Soil compaction, decrease in organic matter and nutrient deficit in soils are considered the main arable soil related problems in Estonia, caused by the lack of classical crop rotation as well as of nutrient balance data and fertilization plans, monoculture cultivation and the decrease in the use of solid manure.

Quality of agricultural land in Estonia

For assessment of soil quality and fertility, various methods and criteria have been used (Andrews et al., 2003). The inital steps in assessing soil quality are to identify the management goals (Wienhold *et al.* 2005). In Estonia, assessment of the soil quality of arable land is made on a 100-point scale. For this, several criteria are employed: soil type, texture, stoniness, thickness of the humus layer, humus content, water regime and drainage condition, relief, field size, etc. Estonian soils are comparatively well studied. Large-scale soil mapping (scale 1:10,000) of the whole territory was completed already in the early 1990s (Reintam *et al.* 2003). This has enabled to assess the quality of arable land for each agricultural field as well as on the regional level. As the renewal of the database of arable land was completed by the Land Board in 1996, the results of the assessment of the quality of agricultural land reflect the state of that time.

The average soil quality of arable land in Estonia is 39 points. The quality of the soil of one-third of arable land is exceedingly low, ≤ 32 quality points. Conventional agriculture on such low quality soils is questionable, as production is ineffective and costly. In 17 rural municipalities average soil quality is below 31 points and in 70 rural municipalities it remains below 36 points (Figure 1). The most fertile soils are found in central Estonia where dominating are *Calcaric Cambisols* and *Luvisols* and their gleyic analogues. *Gleysols* and *Eutric Histosols* account for 16.9% and 7.9% of arable land, respectively. The most widespread soils on Estonian arable land are pseudopodzolic soils.

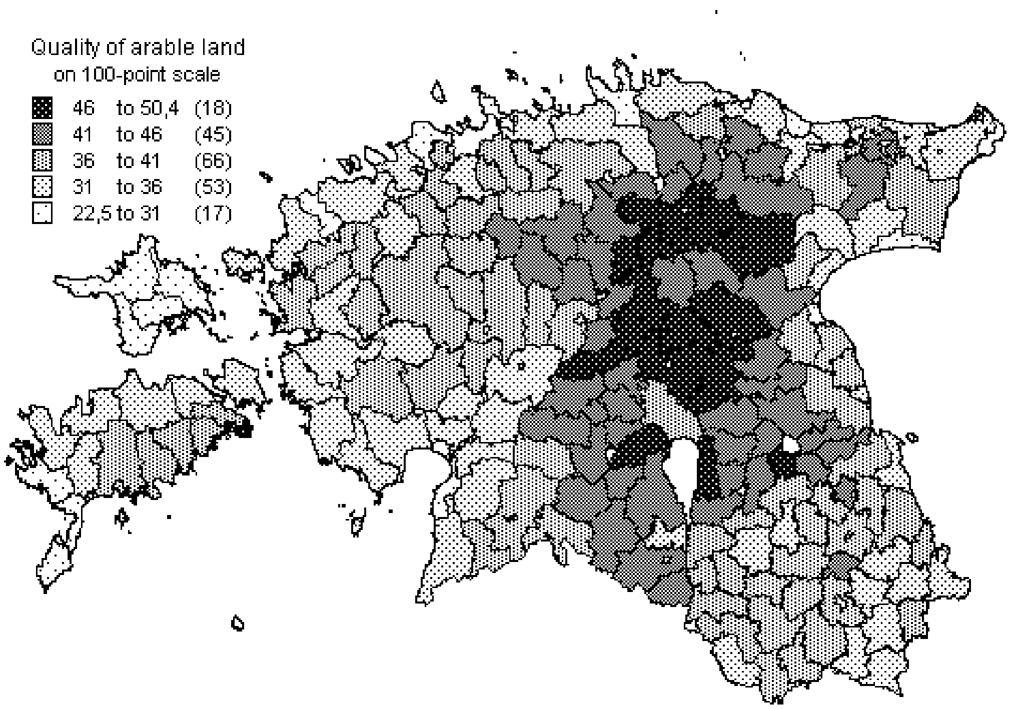

Figure 1. Quality of arable land in different Estonian rural municipalities (on a 100-point scale).

Of the Estonian arable land, 22.6% lies on soils whit humus content about 2% or less. The proportion of the most fertile soils in Estonia, i.e. *Calaric Cambisols* and *Calaric Luvisols*, forms 16%, while their humus content is in the range 2.5–3.5%. The share of relatively drought sensitive *Leptosols* on limestone makes up 9.8% and their humus content may exceed 3.5–4%. Compared with automorphic soils the humus content of gleyic soils is 0.5–1% higher, while the amount of humus in *Gleysols* is 2–3 times higher. Thus the requirement of nitrogen fertilizer is high for 35–40% of arable land. To preserve soil fertility and to ensure increases in yield, the amount of nitrogen supplied as fertilizer should exceed the amount of nitrogen removed with crop by10–30%. There is a high correlation between soil humus and nitrogen content, therefore soil humus content may serve as a basis to determine the requirement of nitrogen fertilizer. The effectiveness of nitrogen fertilizers and therefore also related energy efficiency is often higher on soils poor in humus than on soils rich in humus.

On hydromorphic soils the quality of arable land depends on the drainage conditions. About a half of the Estonian usable agricultural area has been drained but more than 70% of the existing agricultural land drainage systems were established more than 30 years ago and insufficient investments reduce the proportion of lands in good and fairly good drainage condition by approximately 2–3% a year (ERDS 2006).

Soil acidification is a problem which mainly occurs in Southern Estonia. About 40% of Estonian agricultural land needs regular liming. The soil acidification process mainly resulting from soil parent material characteristics cannot be avoided as in Estonian climate conditions where calcium and magnesium carbonate leaching is continuous process. In Estonia, soil liming can maintain the favorable soil reaction level for plant growth and avoid the decrease in the quality of soils. Liming has also been insufficient since 1990 and at present arable soils are degraded through acidification (Loide 2006). This can already in mid-term time scale limit the efficiency of fertilizers and have negative effect on the energy efficiency in plant production. Limestone and dolomite deposits as potential liming materials are mainly located in the northern part of Estonia. Limestone is used as raw material for cement, lime burning, construction stone and broken stone. Dolomite is mainly used as a decorative construction stone. Residues from cement industry are an important resource for agricultural liming.

Soil nutrient balances

A widely accepted approach to evaluate the sustainability of agricultural production concerning the nutrient status is to calculate nutrient balances. Nutrient balances summarise nutrient inputs in and outputs from a defined system over a defined period of time. Balances can be made for all kind of elements, and for all types of ecosystems and scales. Nutrient balances for agricultural soils are usually calculated to evaluate possible change rates of soil fertility (productivity) and to estimate possible losses through nitrogen and phosphorus leaching.

Nutrient balances could be used at different scales: starting from field, farm, catchments, region, to country, and even globally (Sheldrick *et al.* 2002). During the last two to three decades, nutrient balances are being used increasingly by farmers and policy makers at farm and country scales (Oenema *et al*. 2003) and are implemented in several countries to meet environmental targets for nutrient management in agriculture on a voluntary or a mandatory basis (Öborn *et al*. 2003). Decisions based on plant nutrient balances at the national scale must be taken with caution because there is usually a large regional variation. Differences at sub-national scale in nutrient balances are presented in several studies (Smaling *et al*. 1993; de Koning *et al*. 1997; Kopinski *et al*. 2006). Land degradation probably always occurs at a fine spatial scale and is therefore complicated to detect at district or country scale. Actual degradation can be buried in the statistics for larger areas.

There is a variety of methods that can be applied to calculate soil nutrient balances; as a result comparison between studies is complicated due to the differences in the way they are calculated and interpreted. Important differences can occur by taking into account, or not, nutrient losses. Several national scale studies do take nutrient losses into account (Stoorvogel and Smaling 1990; Sheldrick *et al*. 2002) but other methods (i.e. OECD methodology) do not consider nutrient losses and are known as soil surface balances (Parris and Reille 1999).

Globally and also within the EU the problems vary greatly. Agricultural systems with high external inputs result in a positive nutrient balance leading to pollution of ground and surface waters. Agricultural systems with low external input may induce the depletion of soil nutrient stocks and the long-term negative plant nutrient balances threatening production capacity of land (Stoorvogel and Smaling 1990; Bindraban *et al*. 2000). Balanced fertiliser application can help maintain and restore soil fertility (Tilman *et al.* 2002).

Large surpluses of NPK are common for countries with high livestock intensity and hence large quantities of available manure (Sheldrick *et al*. 2002). The occurrence of negative plant nutrient balances of soils used to be the preserve of developing countries in Africa, Latin-America and Asia (Stoorvogel *et al*. 1993; Sheldrick *et al*. 2002) but for the last twenty years a similar tendency has been reported in post-soviet countries in Central and Eastern Europe (Cermak 2002; Tunney *et al*. 2003; Csatho *et al.* 2007) and also in Estonia (Astover *et al.* 2006).

The establishment of straightforward relationships between nutrient surplus, losses and environmental impact is complex. Actual nutrient losses (this means also the energy losses) are dependent on site-specific conditions (Sharpley *et al*. 2000) and balance results should be evaluated with site-specific reference values – i.e. with positive reference values when soil P content is low and negative when soil P level is high. Reference levels for N should depend on the type of agro-ecosystem, climate and soil type. The increase in NO_3^- leaching is, up to optimum application rates of mineral N, minimal but leaching, in the case of over-application, often increases considerably. Hence, the optimisation of fertiliser rates is crucial to minimise environmental pollution and energy losses. Precise fertiliser application based on soil analysis ensures a high profitability of plant production and adoption of N fertiliser rates to the available soil N will reduce potential leaching and improve agronomic and energetic efficiency of fertilisation. The optimal N rate is variable for a specific crop or field and depends on cultivar and pedo-climatic conditions (Astover 2007).

Negative nutrient balances and sub-optimal nutrient inputs to the soil limits crop productivity, causes inefficient use of resources and deteriorates the fertility and productivity of agricultural land. Phosphorus and potassium can accumulate as plant available reserves in many soils when the nutrient balance is positive and both can be released from such reserves when the nutrient balance is negative (Johnston *et al*. 2001).

Significantly positive NPK soil balances in the 1970s and 1980s in Estonia have improved the nutrient supply of arable soils (Astover *et al.* 2006). Nutrient surplus can be explained by the low efficiency of fertilisers in the collective farms and state farms of that time and this caused the pollution of water ecosystems (Nõges *et al.* 2005). The low efficiency of fertilisers and related pollution was linked mainly with inappropriate spreading technology and storage facilities for mineral and organic fertilisers. Soil nutrient balances, in 1990s, became negative due to the sharp decrease in fertiliser application. The emission of pollutants to the environment has decreased and the general state of the environment has improved but at present crop production takes place largely at the expense of the soil resources created by farmers in the 1970s and 1980s. Removal of nutrients from the soil cannot continue indefinitely without depleting the productivity of the soil; nutrients must be replaced.

Agricultural producers can only ensure the maintenance of soil fertility in potato cultivation when they are able to give the required amounts of fertilisers and an active balance of NPK has been maintained at equilibrium in 2001–2003 (Astover *et al.* 2006). The amounts of plant nutrients removed with the yield are, in the instance of cereals, markedly greater than the amounts introduced into the soil with fertilizers. The deficits for N and K are 45% and 47%, respectively, while the deficit is particularly high for P, 69%. The most negative active nutrient balance is for forage crops. Three-quarters of the growing area of cereals (76%) were fertilised in 2001–2003, during which the average rate of mineral nitrogen was 45 kg ha^{-1}. The application of mineral fertilisers for oilseed rape (66 kg N ha^{-1}, 10 kg P^{-1} and 30 kg K ha^{-1}) has been more intensive compared to cereals. Negative PK balances in Estonia are evident especially for grasslands and while more than 80% of the organically farmed area is under grasslands and concentrated mainly in regions with low soil fertility the issue of long-term sustainability of low-input farming practices should be given more prominence.

Soil humus balance

Soil organic matter consists of a variety of components. These include, in varying proportions and many transformation stages from raw plant residues to stable organic matter also referred as humus. In mineral soils and especially in arable soils majority of the soil organic matter is accumulated in humus. Organic matter in soil serves several functions. From agricultural standpoint, it is mainly important for two main reasons: (1) it is a bank for nutrient release through mineralization process; (2) it improves several soil physical, chemical and biological properties. Soil organic matter is derived mainly from plant residues and it contains all of the essential plant nutrients. Therefore, it is a storehouse of plant nutrients. Upon decomposition, the nutrients are released in a plant-available form. The stable organic fraction (humus) adsorbs, holds and releases also plant nutrients. Soil organic matter status can be regulated with organic fertilizers: organic waste can include livestock manures, crop residues, compost, sewage sludge etc. Organic materials improve the condition of the soil is by increasing water infiltration and water-holding capabilities, enhancing aeration, and improving soil aggregation. Organic fertilizers are generally considered more environmentally friendly; however, some organic fertilizers derived from industrial waste may contain toxic substances, such as heavy metals. Usually energy analysis studies do not consider changes in soil humus (organic matter) and nutrient stocks (Hülsbergen *et al.* 2002). Humus and nutrient stocks and their quality have siginficant influence on the crop yields and fertilizer requirements, thus also on the energy balances.

In order to maintain soil humus status in balance, the rate of addition from crop residues and manure must equal the rate of decomposition. Changes in soil humus content are quite complicated to observe because slow temporal change rates. Usually at least 5–7 years is needed to detect significant changes. In long-term IOSDV field experiment located near Tartu initial humus content (ca 1.73%) decreased without organic fertilizers during 18-year period by 0.2% (Figure 2). Periodical application of farmyard manure increased the humus content about up to 1.95%.

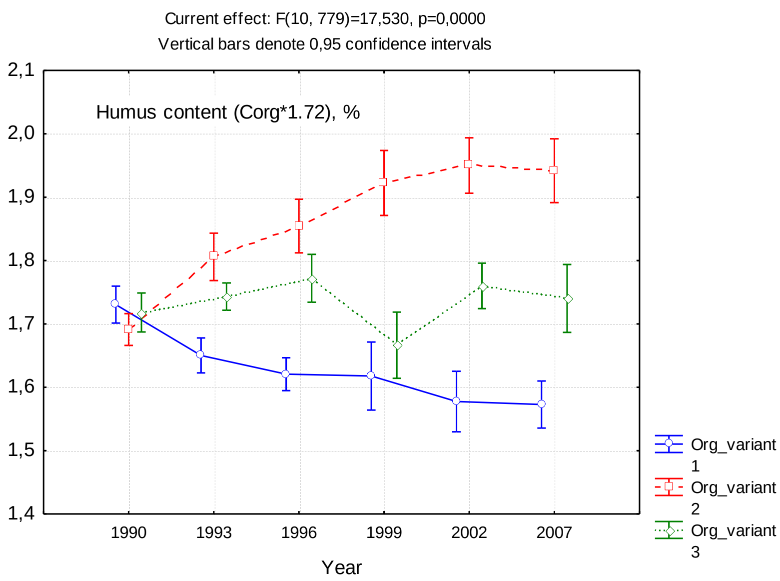

Figure 2. Changes in soil humus content in IOSDV Tartu field experiment (rotation: potato – spring wheat – spring barley) during 18 years depending on the organic fertilizer treatments: org_variant 1 – without organic fertilizers; org_variant 2: solid cattle manure 40–60 t ha^{-1} for potato; org_variant 3: alternative organic fertilizers.

The humus balance approach is based on indirect estimation of humus replacement requirement instead of a direct determination of soil humus content. Humus replacement rate depends mainly on the soil specifics, crop rotation, soil tillage and organic fertilization. Soil humus balance remains negative in growing root crops, potato, cereals and oilseed rape etc. Black fallow has the most negative impact on the soil humus balance (Figure 3). Legumes, permanent grasslands, the use of organic fertilizers can contrary increase soil humus reserves. Humus replacment ability of organic manures is usually estimated acoording to their quality, nutrient content and decomposition rate.

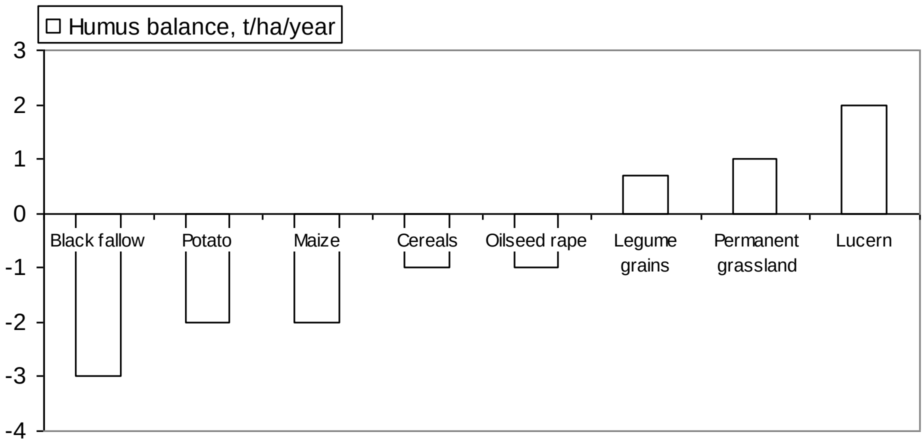

Figure 3. Soil humus balance depending on the land use and crop (after H. Vipper) *conventional tillage

Crop production energy parameters and maintenance of soil productivity

Fertilizers are regarded as a major energy input in conventional agriculture. Production and utilization of mineral fertilizers account for 40–55% of the total energy used in agricultural production in developed countries. In particular, usually nitrogen fertilizers represent largest contribution to the total energy input. Different authors have lead to results that maximum energy gain is obtained at high production intensity, whereas maximum energy ratios were achieved in much lower production intensities (Kuesters and Lammel 1999; Biermann *et al.* 1999; Hülsbergen *et al.* 2002; Rathke and Diepenbrock 2006). Maximum energy gain is desirable when the land is used to produce renewable energy or when the demand for plant production cannot be met because of the limited area of growing crops. Optimizing fertilizer use according to the energy ratio more land will be needed to compensate the yield reduction caused by the relatively low input of fertilizers (Hülsbergen *et al.* 2002). Mikkola and Ahokas (2009) have proved for Finnish conditions that maximum energy ratios are achieved on low fertilizer level. In low-input fertilization plant growth is limited to natural soil fertility and soil nutrient reserves (hence also the production capacity) are depleted in the long-term.

Rossner (2009) showed in the example of IOSDV field experiment (Estonia, Tartu) that optimum N doses for energy parameters varied widely (0...160 kg ha^{-1}). The data of the study were collected from a long-term field experiment with three-field crop rotation (potato - spring wheat - spring barley) in growing period 2006...2008. This experiment was set up on the sandy loam *Fragi-Stagnic-Albeluvisol* by WRB in 1989. For maximizing energy gain optimum N rates were comparable to agronomic optimum fertilizer rates. Energy yield is not linearly correlated with energy input and research has to face the challenges of evaluating production efficiency dependently of input level and soil conditions. The highest values of energy ratio for wheat were obtained at low N input but for barley and potato higher input is necessary (Figure 4). We can conclude that high energy ratio for wheat is attained without fertilization but this kind of land use strategy leads to negative soil nutrient balances and harms crop productivity in short and long term time scale.

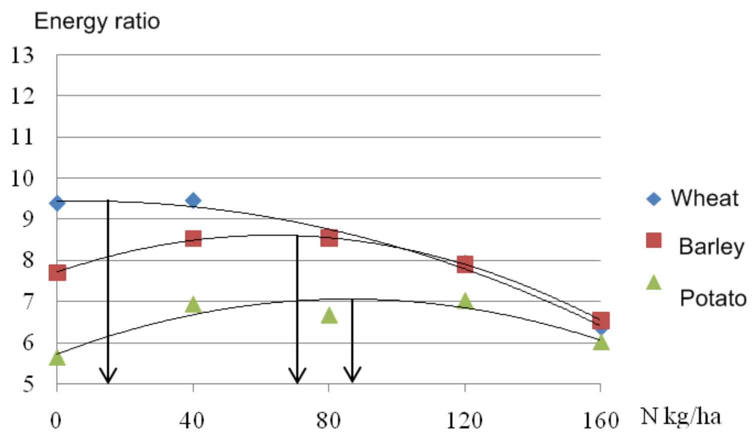

Figure 4. Energy ratio for spring wheat, spring barley and potato in IOSDV field experiment depending on the mineral N input

We calculated for the same experiment annual change rate (%) of grain yield of spring wheat from linear regression (yield versus time as a rotation avarage for each experimental variant, total time scale 18 years). This enabled to estimate which fertilization level is sufficient to maintain or increase long-term production capacity of agricultural land. Wheat production wihtout fertilizers has high energy ratio (Figure 4) but decreased crop productivity by 1.6% per year. Lon-term producivity is maintained at the medium fertilization intensity (83 kg N ha^{-1}) and can even increased at high input levels. Sustainability analysis and land use decisions purely based on the energy parameters are to one-sided and its important to consider also possible effects on soil producivity.

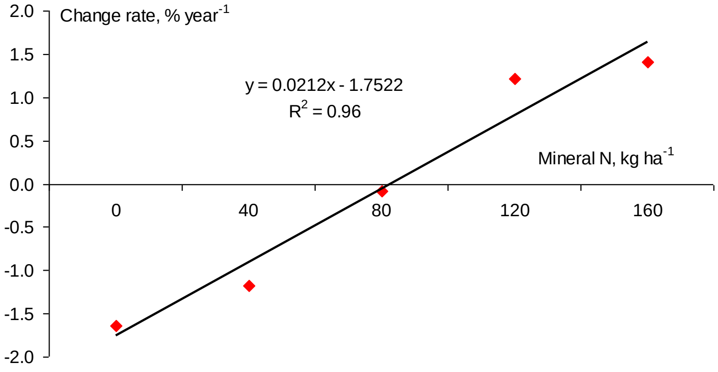

Figure 5. Annualized change rate (% per year) of spring wheat yield in IOSDV field experiment depending on the mineral N input

There are several possibilities simultaneously maintain soil fertility and achieve energy saving:

- tillage methods and its timing
- balanced and synchronized fertilization
- retaining and recycling nutrients and organic matter on-farm
- diverse crop rotation (nitrogen fixing plants, cover crops etc).

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