LAND USE AND SOIL MANAGEMENT IN ESTONIAN AGRICULTURE DURING THE TRANSITION FROM THE SOVIET PERIOD TO THE EU AND ITS CURRENT OPTIMISATION BY THE SPATIAL AGRO-ECONOMIC DECISION SUPPORT SYSTEM

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LIST OF ORIGINAL PUBLICATIONS

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The paragraph *Yield potential and its utilisation* from the paper III is incorporated as a part of this thesis.
1. INTRODUCTION AND REVIEW OF THE LITERATURE

Profound changes have taken place in European agrarian policies in recent years, which have significantly influenced the development of rural areas and agricultural production. The reforms in Central and Eastern European countries (CEECs) were notably large-scale (Sarris et al. 1999; Swinnen 1999; Burger 2001; Turnock 2001). The most acute changes in Estonia’s economy sector during the post-independence transition period occurred in the agriculture sector. The restructuring of agriculture, in the 1990s, was complicated by the disappearance of the former Soviet markets, by the loss of subsidies and by the liberal trade policy implemented in Estonia. The former exceedingly high agricultural subsidies were abolished in the 1990s, in a period of only a few years (Trzeciak-Duval 1999), and land reform and the privatisation of state farms were also carried out (Alanen 1999). The principles of the privatisation of land to its former owners and the lack of rural policy have led to the creation of small inefficient farms (Unwin 1997). The decline in Estonia’s agricultural production in the 1990s was according to Csaki (2000) the most significant among the other post-socialist CEECs. The proportion of agriculture and hunting in gross domestic production decreased from 12.7% in 1990 to 2.4% in 2005. Agricultural employment in Estonia in the same period has decreased from 16.6% to 3.9%. Transitional processes have also worsened the national food self-sufficiency to 75% in cereals and meat in 2000–2004. Only in milk and fish products has Estonia maintained a positive trade balance. The competitiveness of the Estonian agriculture sector has been low since the beginning of 1990s. The net added value of agriculture per labour unit is lower by a factor of five and the total production of the agriculture sector in producer prices per hectare of agricultural land is lower by a factor of four than the average of EU15 (ERDS Annex 2006). Estonia having become a full member of the EU in May 2004 (applied in 1998) has undergone the process of making the transition from the liberal economic policy of the 1990s to the EU’s Common Agricultural Policy (CAP).

Earlier studies have focused mainly on the comparison of the changes that took place in different post-communist states in the transition period (Csaki 2000; Lermann 2000) or analysed the changes in Estonian agriculture at the state level (Roostalu et al. 2000; Yao 2005) and at the county level (Maidre and Lilover 2003; Sepp and Hiinemäe 2003).

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CEECs</td>
<td>Central and Eastern European countries</td>
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<tr>
<td>DSS</td>
<td>decision support system</td>
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<tr>
<td>EU CAP</td>
<td>European Union Common Agricultural Policy</td>
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<tr>
<td>EU15</td>
<td>Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom</td>
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<tr>
<td>EU25</td>
<td>EU15 countries plus Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia</td>
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<tr>
<td>FADN</td>
<td>Farm Accountancy Data Network</td>
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<tr>
<td>GIS</td>
<td>geographical information system</td>
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<td>LFA</td>
<td>less favoured areas</td>
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<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
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<td>PSE</td>
<td>producer subsidy equivalent</td>
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The consideration of regional differences in the assessment of changes in agricultural land use, despite the fact that the pedo-climatic and socio-economic conditions of Estonia vary greatly from region to region, has still been lacking.

Nowadays, increasing attention is given to sustainable and effective use of natural resources (Park and Seaton 1996; Bade and Kruseman 1998). Alternative agricultural systems, which can ensure an ecologically cleaner and healthier environment, have gained significantly more importance (Staniszewska and Schnug 2002; Kirchmann and Ryan 2004). The applied agricultural system determines the efficiency of use of resources (Struik and Bonciarelli 1997; Eltun et al. 2002), the nutrient balance of soils (Schröder et al. 1996; Kücke and Kleeberg 1997; Kätterer and Andren 1999) as well as the general state of the environment and agro-ecosystems (Waldon et al. 1998; Roostalu et al. 2000; Kutra and Aksamaitiene 2003). The proportion of organically farmed land in Estonia has increased from year to year and accounts for 7% of agricultural land in 2006 of which more than 80% is currently under grasslands. Areas covered by various agri-environmental schemes equate to 61% of total supported land.

Pedo-climatic, ecological and economic analyses serve as the basis for promoting both traditional and alternative farming systems. Any farmer in production activity should proceed from the conception of optimiza-


tion. Farmers should have adequate knowledge as well as economic resources for ensuring conditions for formation of an optimal yield, while in the exploitation of these resources an optimal ratio should be reached between economic outcome, quality, production risks and the state of the environment. Efficient use of nutrients is a central component of sustainable cropping systems both in intensive production systems where losses can lead to environmental problems and in low input production systems where soil degradation through nutrient depletion occurs (Gregory and George 2006). Achieving environmental friendly agriculture is crucial not only at a local level but also at a regional level; almost one third of the nitrogen and phosphorus load into the Baltic Sea in 1995, for example, originated in Estonia (Granstedt 2000). A positive effect of the collapse of Estonian agriculture has been a reduction of the pressure on the environment whereas a negative effect has emerged in soil degradation which is due to insufficient investments into maintaining or improving soil fertility. 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). Liming has also been insufficient, since 1990, and while about 40% of arable land requires continuous liming, then at present, arable soils are degraded through acidification (Loide 2006).

Research into soil degradation and sustainable land use is of increasing importance in Estonia. EU CAP cross-compliance and EU agri-environmental policy schemes require that all agricultural land is kept in good agricultural and environmental condition (Van-Camp et al. 2004). The implementation of the EU Thematic Strategy for Soil Protection will further increase the demand for policy relevant soil information (Blum et al. 2004). Soil protection policies need to have a special focus on sustainable use and management of agricultural soils for maintaining the fertility and agronomic value of agricultural land (European Commission 2002).

Sustainable agriculture is the production of high-quality food and other agricultural products and services in the long term, with consideration taken to economy and social structure in such a way that the resource base of non-renewable and renewable resources is maintained (Agenda 21… 1998). Sustainable agriculture is aimed at (i) securing the food supply on a long term basis, (ii) preserving soil fertility as a basis for life and economic activity for future generations, (iii) efficient use of renewable resources without exceeding their regeneration capacity, (iv) protection of non-renewable resources, (v) preservation and development of biodiversity and rural landscape, (vi) securing animal welfare and species protection, (vii) increased public awareness on sustainable issues, equitable relations in trade of products at the local and international level, (viii) development of rural communities (Agenda 21… 1998). All these aspects of sustainable agriculture have been influenced by large-scale changes during the transition period in Estonia and the need for knowledge-based optimisation of agricultural land use and soil management has become more important. There is a necessity to analyse the impact of agricultural collapse on land use, resource use efficiency and soil degradation.
1.1. Plant 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 kinds 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 and to estimate possible losses through nitrogen and phosphorus leaching. A quantitative knowledge of the depletion of plant nutrients from soils aids the understanding of the state of soil degradation and promotes the selection of sustainable nutrient management strategies.

Nutrient balances could be used at different scales: starting from field, farm, catchments, region, to country, and even globally (Sheldrick et al. 2002; Öborn et al. 2003). 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). Warren (2002) argues that 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 plant nutrient balances; as a result comparison between studies is complicated due to the differences in the way they are calculated and interpreted (Öborn et al. 2003). This is partially a result of the lack of well-established and overall approved guidelines for their use (Oenema et al. 2003). Tunney et al. (2003) reported variability in calculations of phosphorus balance at the field scale between European countries. 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 (Sibbesen and Runge-Metzger 1995; 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 future agricultural production (Stoorvogel and Smaling 1990; Bindranab et al. 2000). Balanced fertiliser application can help maintain and restore soil fertility (Tilman et al. 2002). Tan et al. (2005) calculated global soil nitrogen (N), phosphorus (P), and potassium (K) budgets for wheat, rice and barley for the year 2000. They found global soil nutrient deficits (kg ha⁻¹ year⁻¹) of 18.7 N, 5.1 P and 38.8 K. Sheldrick et al. (2002) found that world average soil depletion of nutrients in 1996 was estimated at 12.1 kg N ha⁻¹, 4.5 kg P ha⁻¹, and 20.2 kg K ha⁻¹. Both studies (Sheldrick et al. 2002; Tan et al. 2005) highlighted the importance of large regional differences. There was unbalanced over-fertilization with a surplus in some developing countries whereas insufficient inputs occurred in many developing and all the least developed countries. 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 fifteen years a similar tendency has been reported in post-soviet countries in Central and Eastern Europe (Cermak 2002; Tunney et al. 2003; Kudeyarov and Semenov 2004; Karklins and Līpenite 2005; Nikolova 2005) and also in Estonia (Löfgren et al. 1999; Kärblane et al. 2002). Previous studies have presented nutrient balances of Estonian arable soils for a limited time period (Piho 1976; Raudväl 1985b; Kärblane and Kevval 1988; Kärblane et al. 2002) whereas Sheldrick et al. (2002), by contrast, argue that to quantify soil degradation caused by nutrient depletion, it is essential that nutrient balances are calculated and compared over time. There is, therefore, a need for analysis of the long-term nutrient balances of arable soils in Estonia.

The establishment of straightforward relationships between nutrient surplus, losses and environmental impact is complex (Öborn et al. 2003). Actual nutrient losses are dependent on site-specific conditions (Sharpley et al. 2000; Hatch et al. 2004) and Janssen (1999) suggested that balance
results should be evaluated with site-specific reference values – 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. Oenema et al. (2003) stated that in The Netherlands surplus reference values are based on political decisions, weighting agro-economic consequences versus environmental consequences. Nitrogen may leach to the water ecosystems or be lost through gaseous emissions of ammonia and nitrous oxides. Denitrification and leaching values are related with large uncertainties with a coefficient of variation over 30% (Oenema et al. 2003). N balances show the potential for pollution but not the actual pollution (Parris 1998). Models have been developed in several studies that relate N surplus with nitrate loss (Granlund et al. 2000; Salo and Turtola 2006). Salo ad Turtola (2006) stated that soil N balance is an especially useful indicator when cultivation techniques included environmentally hazardous management. Commonly soil surface balance is held to be an appropriate indicator for potential nutrient losses from soil. Mander et al. (2000) showed that in small agricultural sub-catchments the rate of fertilisation is the most important factor affecting nitrogen runoff and argued that the decrease in fertilisation in the 1990s has reduced nutrient losses. The increase in NO\textsubscript{3} leaching is, up to optimum application rates of mineral N, minimal but leaching, in the case of over-application, often increases considerably (McNeill et al. 2005). Hence, the optimisation of fertiliser rates is crucial to minimise environmental pollution.

The transitional period has induced changes in fertilisation intensities and consequently in the nutrient balances of arable soils in Estonia (Roostalu et al. 2000). Negative nutrient balances and sub-optimal nutrient inputs to the soil limits crop productivity, causes insufficient use of resources and deteriorates the fertility and agronomic value 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 (Piho 1977; Kärblane et al. 1978; Johnston et al. 2001). Phosphorus limits crop yields on 30–40% of the world’s arable soils (Kirkby and Roemheld 2006) and a similar situation is also evident in Estonia, where the content of lactate soluble phosphorus is low or very low for 28.9% of arable soils (Järvan et al. 2004). Worldwide the largest P surpluses are recorded in areas with intensive livestock production and high animal density (Djodjic et al. 2005). Saarela et al. (2004) showed in a study on twenty-two diverse Finnish soils that at zero balance, at which the applied P fertiliser exactly replaced the P removal with harvested crops, most of the initially low P values remained unchanged but decreased in the case of higher initial values. The annual surplus of the P balance should be 6 kg ha\textsuperscript{-1} in phosphorus poor soils and 15 kg ha\textsuperscript{-1} in phosphorus rich soils, to prevent the slow decrease of the soil P content extracted with acid ammonium acetate (Saarela et al. 2004). The precise replacement of P removal by crops was also insufficient to maintain soil P status in a long-term experiment on five various soils in Sweden (Djodjic et al. 2005). Ehler et al. (2006) found in an eight-year long field experiment a significant decline in soil P status in the upper 5 cm layer at surpluses below 20 kg P ha\textsuperscript{-1} but P status of deeper soil layers remained virtually constant. First year yields in organic systems are commonly achieved at the expense of soil reserves or residual P from previous fertilisation (Oehl et al. 2002). Piho (1977) states that in the case of unfertilised treatment, the utilization of the soil P supplies can be planned without essential yield loss, 10% of lactate soluble P on light and medium texture soils and 5% of lactate soluble P on clay soils. Long term experiments in England showed that the omission of P and K fertilisers will lead to yield losses once available soil P and/or K reserves have declined below the critical level appropriate for the soil and cropping system (Johnston et al. 2001). Lauringson et al. (2004) found in crop rotation experiment that the soil available P content decreased when P input was 87–130% compared to P removal with harvested yield and increased when P input was double compared to removal with yield.

The impact of fertilisation strategies and cropping systems on the soil exchangeable K concentration differs between soil texture classes (Kärblane et al. 1998; Andersson et al. 2007). The adsorption of K onto exchange surfaces and its availability is very dependent on the physico-chemical properties of the soil (Syers 1998). Holmqvist et al. (2003) have estimated that in northern European soils K release from mineral weathering varies 3–82 kg K ha\textsuperscript{-1} annually. Piho (1977) found in a crop rotation experiment in Estonia that in unfertilised soils 30–45 kg K ha\textsuperscript{-1} was released which constitutes 10–30% of soil lactate soluble K reserves. Clay-rich soils can potentially supply crops with enough K but coarse, sandy and organic soils have very low weathering potential and external inputs of K are essential (Öborn et al. 2005). A farming system with zero or even only replacement of K off-take is not sustainable on coarse textured soils and moreover these soils need additional K fertiliser to maintain optimal soil
exchangeable K content, but silty clay and clay soils appeared most suitable in maintaining adequate soil K level where no or small applications of K fertiliser are made (Andersson et al. 2007).

1.2. Determinants of agro-economic performance of farming

Economic indicators are used as one criterion to evaluate farming sustainability (Freyenberger et al. 2001). Profitability is the most central economic prerequisite for continuing business. Variations in farm of agro-economic performance may be explained by (i) internal structure and agency factors of farm and (ii) inter-organisational arrangements (Gorton and Davidova 2004). Farmers have no direct control over factors external to their operations but they can manage internal resources.

Agricultural policy and subsidies have significant impact on the farm economics. Producer subsidy equivalent (PSE) is a widely accepted measure of the extent of agricultural subsidization (Cahill and Legg 1989). Expressed as a percentage PSE shows which part of the value output is accounted by various support. There has been an increasing trend in last few years to link subsidies with agri-environmental schemes. Only a few developed countries have low PSE (i.e. New Zealand) but EU15 countries have PSE over 40%. The proportion of subsidies from total income on Finnish cereal farms varies from 35-53% (Kaljonen 2006). PSE can even be negative in some developing and transitional economies. This means that farmers are being taxed instead of subsidized. The agricultural support measured by PSE was much lower in transition period CEECs than the average in EU15 and OECD countries (Zawojka 2002). Macours and Swinnen (2000) estimated that the drop in agricultural output in CEECs during 1989–1995 has resulted mainly from price and trade liberalization and the reduction of subsidies. Ivanova and Lindgard (1994) found negative PSE for a wide range of agricultural commodities in the beginning of 1990s and this resulted in low levels of profitability in Bulgarian agriculture. Negative PSE also occurred in 1992–1994 in Estonia (Trzeciak-Duval 1999; Pouliquen 2001); this was followed by an ultra-liberal agricultural policy and low subsidization during the pre-accession period to the EU. The implementation of the EU CAP, in Estonia, in 2004 increased the role of subsidies and subsequently farm economic performance is strongly related to ongoing EU CAP reforms. Up to the present the influence of the Europeanization of Estonian agricultural policy on agricultural land use and soil management has been not studied. Profitability of agriculture and consequently agricultural policy affects changes in land use and farming practices. Therefore integrated analysis of land use and soil management in Estonian agriculture during the transitional period, as well as further production optimisation must consider socio-economic aspects.

Location and natural conditions are major determinants of farm profitability, especially in crop production. Soil quality as the determinant of long-term profitability can be regulated through choice of appropriate crop rotation (Karlen et al. 2006), soil management (Liu and Duffy 1996; Katsvairo and Cox 2000), and fertilisation (Halvorson et al. 2001; Cherr et al. 2006). Short-sighted or improper soil and crop management decisions can lead to resource degradation (Karlen et al. 2006) and limit farm economic viability in the future.

The optimum level of production (yield level) is the point where it is unnecessary to add any more inputs. This is because the costs of adding any more inputs will be higher than the returns. The law of diminishing returns means that after a certain yield level, the increased inputs are followed by diminished increase or even by yield decrease (Kho 2002). The law of diminishing returns should be a basic instrument of choosing farming intensity level in agricultural production, guaranteeing maximum revenue for a producer (Szarek 2005). Managed inputs (labour, seed, fertiliser etc) are factors that ultimately affect yield. Other factors of production, such as rainfall, temperature, and various soil characteristics, are not managed by farmers but still affect yield. Economic variables, particularly managed input prices and product prices, are important elements in the process of input optimisation. Achievement of optimal resource use is possible only if the resource is available in sufficient quantity or only if the farmer has sufficient current assets or available budget to buy it in sufficient quantity. The sub-optimal use of variable inputs like fertilisers occurred, for example, in Estonia in the 1990s when increasing input prices were not balanced by rising output prices and consequently the farming sector had a deficiency of current assets (Roostalu 2001). Matvejev (2007) showed that in 2005 better net added value per annual working unit and profitability occurred in farms where costs per hectare were higher. This indicates that sub-optimal intensity of production inputs is often a reason for the low competitiveness of Estonian farming.

Farmers need to know the yield response function to make decisions about optimal inputs levels. They, therefore, need information about how
yield will respond to different rates of application of the managed inputs, as well as to different pedo-climatic conditions, etc. and the interactions between managed input rates and non-managed factors (Bullock and Bullock 2000). Farmers vary in their managerial ability and their knowledge. Therefore, to improve low profitability and competitiveness of Estonian farming sector (Maidre and Lilover 2003) the input use decisions should be supported by knowledge-based agro-economic models.

1.3. Crop productivity and yield gap

Kropff et al. (1997) stated that the sustainable agricultural development should decrease differences between attainable and actual yield levels through increased efficiency of resource use. The yield potential can be estimated on experimental yields and is associated with specific soil and weather conditions that can change (Dahnke et al. 1988). Actual yields may range from zero to potential. The yield gap is the difference between the yield potential and the average yield achieved in actual farming conditions. The yield potential can be compared with actual national average yield to give some idea of the yield gap that can be bridged. Actual yield levels are not only influenced by bio-physical resources, but also, and often even more strongly, by socio-economic conditions (Bindraban et al. 2000). Farming practices may not meet the agronomic conditions needed to realise potential yield levels for existing eco-physiological conditions. There is on-going discussion as to whether it is relatively more important to further improve yield potential genetically, or agronomically, reducing the gap between this potential yield of modern cultivars and actual yields achieved on farms (Otegui and Slafer 2004). Actual yields in most of the cereal growing regions of the world constitute only a small proportion of potential levels and expansion through management improvement can be more relevant. Actual yields in intensive production areas with irrigation are reaching 80% of the yield potential (Cassman et al. 2003) so further development of genetic yield potential is crucial. Nevertheless, even a technologically progressive country such as France is not yet close to reaching its yield potential. France could obtain an average wheat yield of 8.7 Mg ha\(^{-1}\) but the actual average yield is currently 7.2 Mg ha\(^{-1}\) (FAO World Agriculture… 2002). Low utilization of yield potential is often due to the differences in crop management practices, such as the amount of fertiliser used. Dobermann and Cassman (2002) have estimated that farm yields must account for 70–80% of the yield potential to cover increasing world food demand. Decisions concerning crop management, i.e. fertiliser application, timing of weeding and crop protection measures, and seeding dates, do influence to what extent the yield potential will be realized (Penning de Vries et al. 1997). The lowest yield level of crops in Estonia compared to other European countries (Roostalu 2001) indicates that there exists a high yield gap. This causes ineffective use of pedo-climatic resources and deterioration in agricultural self-sufficiency. In 2000–2003 the domestic use of cereals was 740.5 thousand Mg but total production of cereals was only 571.4 thousand Mg. Vasiliev et al. (2003) showed on the example of Estonian grain farms that the yield of cereals depends on the specific costs for cereal cultivation (\(r = 0.80\)) and Matvejev (2007) found that good economic performance is related to higher yields. To achieve higher crop productivity simultaneously with economical and environmental benefits, the production inputs should be optimised in a temporal and spatial scale. Hence, the development of a contemporary decision support system for farmers is crucial to increase the sustainability of Estonian agriculture.

1.4. Decision support systems in agriculture

Decision support systems (DSS) in the broader term, are any method by which information can be transmitted, shared or structured to help their users arrive at a decision (Stone and Hochman 2004). DSS, more specifically, are computer-based frameworks for integrating data and expert opinions with models, which enable finding different solutions when analysing a particular problem and often with geographic information system (GIS) linkages provide spatial recommendations (Fischer et al. 1996). DSS are most likely to be useful for delivering information to farmers if they provide information for farmers to use in their own decision making processes, rather than providing them with an explicit answer (Stone and Hochman 2004). There are several approaches to combine GIS with modelling (Sui 1998) and loose coupling that integrates GIS with analytical models through the exchange of data files requires little investment in software development (Matthews et al. 1999).

Spatial DSS are applied in several branches: like land use planning (Matthews et al. 1999; Ceballos-Silva and Lopez-Blanco 2003) and land allocation (Carsens and Knaap 2002; Wang et al. 2004), fertilisation (Tianhong et al. 2003), biomass production (Voivontas et al. 2001), environmental protection (Aspinall and Pearson 2000), nutrient balances (Sacco et al. 2003), nature conservation (Geneletti 2004), forest management (Rey-
nolds 2005) and afforestation of former farmland (Gilliams et al. 2005).

The acceptance of DSS by farmers, despite the presence of numerous DSS developed for agriculture worldwide, has generally been low, with certain exceptions (McCown 2002). Agricultural DSS are developed for specific purposes like NGAUGE in England for grassland N optimisation (Brown et al. 2005) or for complex farm advising like PI@ntelInfo in Denmark (Leck Jensen et al. 2000) and AgriSupport in Spain (Recio et al. 2003). A computer-based DSS for plant protection named “I-Taime-kaitse” has been applied in Estonia since 2002 (Kastanje and Lõiveke 2006). “Talutark”, an integrated computer program, was developed in the mid 1990s and was initially used for economic book-keeping but was later expanded as a crop and animal husbandry data handling tool (Rütel 1997). Nevertheless, up to the present there is, in Estonia, a lack of spatial DSS based on crop response models for agricultural land use and soil management optimisation.

Farm management recommendations should be determined by applying sound economic and environmental protection theory to data from agronomic experiments. Agronomic data are valuable to estimate the relationship between crop yields, managed inputs, soil characteristics, and weather variables (Bullock and Bullock 2000). DSS requires reliable crop response models to assess the impact of specific land management (Park et al. 2005). Precision agriculture and its most common approach for variable rate fertilisation (Bongiovanni and Lowenberg-Deboer 2004) has made information from agronomic experiments even more valuable (Bullock and Bullock 2000). One of the main reasons for the lack of model based DSS is that input values for models are unavailable, expensive or difficult to collect (Parker and Campion 1997). A large-scale soil map and supplementary databases form an important component in decision making for land use planning and utilisation of resources (Reintam et al. 2003). Manderson and Palmer (2006) argued that soil related models will become increasingly important decision-making resources for agriculture and the value of soil information can be realised only when it is actually used. Only a few European countries have complete (or near-complete) national soil survey coverage at scales 1:10,000 and larger (Bullock et al. 2005) which were applicable in field-scale DSS. Up to 1992 the Estonian soil cover was mapped completely at scale 1:10,000 (Reintam et al. 2003) and these maps have been digitalized for current use. Concurrent with large-scale mapping an assessment of the quality of arable soils was carried out. The systematic assessment of fertiliser requirement and detailed agrochemical mapping of Estonian soils was started in 1957. Thereafter soil fertiliser as well as lime requirements have been determined on six occasions. Despite the fact that regular soil surveying ceased in the 1990s, valuable soil databases and maps do exist which can be used as initial data sources for land use and soil management optimisation. The application of collected soil information has still been modest because of the complicated availability and limited knowledge of the decision makers (Kõlli 2001). To overcome these shortcomings the soil information can be valued, made easily available and self-explanatory through contemporary DSS.

The Estonian Research Institute of Agriculture used electron computers for field-specific fertiliser application planning for the first time in 1973 (Piho et al. 1976). The fertiliser planning models were developed for thirty-five crops, for five soil P supply levels and for four soil K supply levels (Kevvai et al. 1975). The regression equations for N optimisation were calculated considering soil humus content (Piho 1975). Fertiliser application plans for ninety-eight collective farms were ready for use in 1975 (Piho et al. 1976) but their practical application remained modest. Fertilisation decisions in current use in Estonia are mainly based on the yield-oriented recommendations from handbooks (Kevvai and Kärblane 1996; Rooma and Toomsoo 2002; Kanger et al. 2003). These fertiliser recommendations are provided for limited soil nutrient supply levels and do not take into account economic criteria. Olfs et al. (2005) argued that fertiliser recommendations based only on a fixed yield goal with a given nutrient off-take have to be regarded as inappropriate. There is, therefore, a requirement in Estonia for a more sustainable fertiliser recommendation system supported by crop response, economic, and environmental models operating in time and space.

1.5. Crop response models to fertilisers

Precise fertiliser application based on soil analysis ensures a high profitability of cereal production (Mengel et al. 2006) and adoption of N fertiliser rates to the available soil N will reduce potential leaching and improve agronomic efficiency of fertilisation (Kutra and Aksomaitiene 2003). The optimal N rate is variable for a specific crop or field and depends on cultivar and pedo-climatic conditions (MacKenzie and Taureau 1997). The total amount of N in soil can be significant but for fertiliser recommendations it is necessary to determine the quantity of N pool that may through mineralization become available during the vegetation period.
(Rice et al. 1995). This approach is well-adopted in several countries and besides the negative aspects of being costly and time-consuming there is a key drawback in that it does not consider potential N mineralization during the growing season (Olfs et al. 2005). Olfs et al. (2005) concluded that best practice should consider soil and plant status. Optimum fertiliser norms can be determined by fitting statistical models to yield data collected from fertilisation experiments. Regression analysis is usually applied to characterize the statistical relationship between controlled variables and crop yield (Park et al. 2005). Derived functional equations are locally specific and therefore complicated to extrapolate to other areas (Jame and Cutforth 1996). This raises the need for development of DSS based on the local experiments. Many nonlinear functions have been used to predict crop yield response to applied fertiliser. Accurate estimates of the parameter values are required for the formulation of satisfactory fertiliser rate recommendations (Makowski and Lavielle 2006). Model selection has remarkable effects on fertiliser recommendations (Webb et al. 1998) and different models with similar coefficients of determination ($R^2$) can result in various optimal fertiliser rates (Cerrato and Blackmer 1990). Danish N fertiliser recommendations apply cubic polynomial response curves for various crops and Beattie et al. (2005) concluded that it often works well when care is taken to avoid extrapolation outside the data domain. Fertiliser response functions are usually estimated statistically in quadratic form, which enables the incremental responsiveness of the crop to decline as larger rates of fertilizer (Dawe and Dobermann 1999) and Bélanger et al. (2000) showed that the quadratic model is the most appropriate for describing the potato yield response to N fertiliser. Fertiliser application planning in Estonia that started in 1970s was also based on quadratic response curves (Piho 1975). Nowadays more data of agronomic field experiments is available to develop detailed crop response models but until now the possibilities of modern information technology for this purpose has been underexploited. Integration of improved crop response models with economic and environmental criteria in spatial DSS can provide a solid basis for achieving more sustainable fertilisation.

2. SET OF THE HYPOTHESIS AND AIMS OF THE STUDY

One hypothesis of this study is that land use and soil management changes occurring in the transitional period from the Soviet regime to membership of the EU have decreased the sustainability of Estonian agriculture. This decrease is due to soil degradation resulting from nutrient depletion and the ineffective use of pedo-climatic resources. The second hypothesis is that changes in arable land use were caused by the socio-economic transition but regional differences in the changes were influenced by the local pedo-climatic conditions. The third hypothesis is that the possibility exists in Estonia to develop the framework for a spatial DSS which promotes (i) increases in low crop productivity, ii) optimisation of inputs and profitability without negative impacts on the surrounding environment, and (iii) improvements in the process of agricultural land use planning.

In order to study these hypotheses, the purposes of the current study were:

- to investigate the changes in arable land use, fertilisation and plant nutrient balances of arable soils (II)
- to investigate the realisation of yield potential of crops (III)
- to analyse the efficiency of mineral fertilisers depending on pedo-climatic conditions (I, IV)
- to analyse the influence of natural and economic conditions on the optimisation of fertilisation and crop production (I, IV)
- to investigate the application and development of agro-economic models for optimisation of fertilisation and agricultural land use planning on the example of spring barley (I)
- to develop the framework for a spatial agro-economic decision support system which serves as a basis for achieving the goals of sustainable agriculture (I).
3. MATERIAL AND METHODS

3.1. Changes in agricultural land use (II)

Changes in agricultural land use were estimated on the basis of national statistics, 1919–2003, and the databases of the Estonian Land Board (Eesti Maa-amet). A database at rural municipality level was created to study regional differences in land use changes after Estonia re-independence in 1991. Arable land in rural municipalities in 1992 was derived from the databases of the Estonian Land Board and in 2001 from databases of the Estonian Statistical Office (Eesti Statistikaamet) based on the agricultural census in 2001.

3.2. Nitrogen, phosphorus and potassium balances of arable soils

The nitrogen, phosphorus and potassium balances of arable soils in Estonia were calculated at the national level on the principal of soil surface balance (II). Nutrient losses were not considered in balance calculations. These calculations were based on the data of national statistics for fertilisation, cropping pattern and crop yields, 1939–2003. Prior to this study, several authors (Piho 1976; Raudvääli 1985b; Kärblane and Kevvai 1988; Kärblane et al. 2002) have calculated plant nutrient balances of arable soils in Estonia for shorter time periods.

Total nutrient balances were calculated as the difference between the input with inorganic fertilizers, seeds, manure, precipitation (for N) (Frey et al. 1988; Kärblane et al. 2002), microbiological fixation (for N) and removal of nutrients with harvested products. Microbiological N fixation is estimated as a fixed percentage of the total nitrogen uptake of leguminous crops (Piho 1967) and depends on the cropping pattern. Removal of nutrients with harvested products is derived from crop specific nutrient contents (Kevvai and Kärblane 1996) and yield figures from agricultural statistics.

Active balances were calculated on the basis of the inputs of plant available nutrients. For determination of the utilization rates of nutrients, originating from different sources, by crops, and for estimation of the impact of the nutrient balance on soil fertility, the results of agronomic field experiments conducted in Estonia over a period of eighty years were summarized (Piho 1973, 1974a, 1974b, 1977; Piho and Ojaveer 1975; Lauk 1977; Kärblane 1978, 1982, 1985, 1986, 1990, 1991; Valgus 1982, 1984, 1985, 1988, 1994; Sirendi 1981; Laur 1983; Raudvääli 1985a; Kevvai et al. 1985; Kärblane et al. 1999, Kanger et al. 2002). Utilization rates of N from mineral fertilisers and precipitation input was 55% and for organic N inputs 50%. Utilization rates of K from mineral and lime fertilisers was 70% and for organic inputs 75%. Utilization rates of P from mineral and lime fertilisers was 35% and for organic inputs 50%. Changes in nutrient supplies of arable soils were estimated on the basis of the databases of the Estonian Agricultural Research Centre (Eesti Põllumajandususuringute Keskus).

3.3. Yield potential and its realisation (III)

The analysis of agronomic efficiency and the economic criteria of grain farms required that the results of crop variety comparison tests of cereals, performed in Estonia over a twenty year period, 1983–2003, national crop yield statistics and the data of the survey of the Farm Accountancy Data Network (FADN) for 2000–2003 were summarised. The yield potential of cereals and oilseed rape was provisionally equated with the yield obtained in the crop variety comparison tests. The realization of yield potential is estimated through differences between yields in comparison tests and national average yields. The actual farm yields and national average can differ significantly (Dawe and Dobermann 1999) and therefore the yield level in specialised FADN grain farms whose grain production (cereals, legumes and oilseed crops) contributed more than 75% to total output was also analysed. The whole analysed sample consisted of 287 observations. This approach enabled the analysis of the agro-economic parameters of specialised grain producing farms, for which correlation analysis was applied.

3.4. Assessment of soil quality

Various methods and criteria have been used for the assessment of soil quality (Bouma et al. 1998; Bindraban et al. 2000). The initial steps in assessing soil quality are to identify management goals (Wienhold et al. 2005). The assessment, in Estonia, of the soil quality of arable land is performed on a 100-point scale, and this indicator describes the productivity of soils. Several criteria are employed for this purpose: soil type, texture, stoniness, the thickness of the humus layer, humus content, water regime and drainage condition, relief, field size, etc (Kask 1975; Kask
1994). The establishment of reference tables to determine quality points for each mapping unit was based on various field experiment and actual farming data. Soil quality points are determined for each soil-mapping unit; further it is possible to calculate weighted average soil quality for each management unit or a region. Data on the quality of arable land were drawn from the Estonian Land Board (I, II).

3.5. Agronomic and economic models

Crop response (agronomic) models were obtained from the regression analysis of numerous different field experiments conducted in Estonia since 1920s. The relationships between spring barley yield, soil properties, climatic conditions, and fertilisation were established using a database containing the results of more than 600 field experiments (I) (Pill 1935; Küüts 1970; Kendra et al. 1971; Piho 1973, 1974a; Kallas 1978; Viil 1979; Ojaveer 1979, 1984, 1986; Raudvåli 1980, 1984; Küüts 1982; Lepajõe 1986; Tikk 1986; Makke 1992; Ameerikas 1993; Nurmekivi 1997, 1998, 1999; Kuldkepp et al. 1998; Kuldkepp and Toomsoo 1999). The database, which contains the results of more than 250 field experiments (Aamisepp 1939; Eesti põllumajandusteadus… 1946; Ümarik 1946; Talpsepp 1966, 1969, 1970; Viileberg 1966; Sutter 1967; Sirendi 1969; Türbas 1969; Sepp 1972, 1974, 1978; Piho 1971, 1973, 1974b, 1977, 1978; Aamisepp 1973; Kang 1987; Kärblane and Tartlan 1989; Tartlan 1989; Valgus 1992; Toomsoo 1998; Kuldkepp et al. 1999) conducted in Estonia with medium or late maturing potato varieties, was used for assessing the impact of soil and climate conditions on the effectiveness of fertilizers (IV). These experiments have been carried out on soils with very different texture and other properties.

3.5.1. Effectiveness of mineral fertilisers

The average effectiveness of mineral fertilisers shows the ability of the plant to increase yield in response to applied nutrient and is also known as agronomic efficiency. The average effectiveness (kg yield per kg applied nutrient) is calculated as the difference between grain yield of barley (I) or tuber yield of potato (IV) on fertilised and non-fertilised plots and divided by the applied nutrient rate.

The estimation of the effectiveness of mineral N, K and P fertilisers on potato (IV) and spring barley (I), depending on soil nutrient supply, and the effect of climatic conditions was based on regression analysis which has the following general form of the equation:

\[ y = a_0 + a_1N - a_2P + a_3P^2 - a_4P^4 \]

where \( y \) is average effectiveness of fertilizer rate \( N_{60} \), \( K_{50} \) or \( P_{25} \); \( x \) is soil humus content (%) or soil lactate soluble K or P content (mg kg\(^{-1}\)), and \( P \) is probability (%).

For example, the effectiveness of mineral \( N_{60} \) fertiliser for spring barley (I) was estimated with the following regression equation (\( R^2 = 0.68; se = 5.98; p < 0.000 \)):

\[ Y'_{60} = 38.649 - 1.744H - 0.487P + 0.0033233P^2 - 0.0000001677P^4 \]

where \( Y'_{60} \) is average effectiveness (kg kg\(^{-1}\) N\(^{1}\)) of the nitrogen fertiliser norm \( N_{60} \), \( H \) is soil humus content (%) and \( P \) is probability (%).

3.5.2. Yield of spring barley (I)

The yield of spring barley was found for the non-fertilised variant and for the fertilised variant. The yield in the case of the non-fertilised variant depends on soil quality. To simulate non-fertilised yield of barley depending on the soil fertility and to estimate weather related variability the following regression equation (\( R^2 = 0.84; se = 0.318; p < 0.000 \)) was applied:

\[ Y_0 = 1.288 - 0.0343SQ - 0.0383P + 0.0002811P^2 - 0.00000001635P^4 \]

where \( Y_0 \) is the yield for non-fertilised barley (Mg ha\(^{-1}\)), \( SQ \) is soil quality points and \( P \) is probability (%). Probability at 50% is used in this study, which represents yield as an average over many years.

The yield in the fertilised variant includes also an increase from the addition of an economically effective norm of NPK. The use of an agronomically effective fertiliser norm ensures the highest profit. The agronomically and economically effective fertiliser norms for barley are calculated from the quadratic yield response curves for different soil nutrient supply levels (\( R^2 = 0.93–0.99; se = 0.1–0.15; p < 0.05 \)). A general form of the quadratic yield response equation is the following:

\[ Y = a_1 + a_2x - a_3x^2 \]

where \( Y \) is the yield (Mg ha\(^{-1}\)) and \( x \) is amount of fertiliser (kg ha\(^{-1}\)).

The agronomically effective amount of fertiliser (kg ha\(^{-1}\)) is calculated as follows:
and the economically effective amount of fertilizer (kg ha⁻¹) is calculated as follows:

\[ X_{\text{eon}} = \frac{a_1(P_y - C_b) - C_f}{2a_1P_y - C_b} \]

where \( P_y \) is the price of the yield (€ Mg⁻¹), \( C_f \) is the cost of fertilisation (€ kg⁻¹) and \( C_b \) is the cost of harvesting (€ Mg⁻¹).

### 3.5.3. Economic criteria

The profit in barley cultivation (I) is calculated as the difference between gross income and gross costs. To calculate the profitability of barley cultivation (\( R_t \), %), we used the following formula:

\[ R_t = \left( \frac{P_y Y}{C_f X + C_b Y + C_o} \right) - 1 \times 100 \]

where \( C_o \) denotes all other production expenses (€ ha⁻¹) such as salaries, depreciation etc.

Profitability in percentages describes the ratio of the profit to the gross costs. In the economic calculations, 109 € Mg⁻¹ was taken as the selling price of barley (\( P \)), 19 € Mg⁻¹ as the harvesting expenses (\( C_b \)), N 0.45, P 1.92, K 0.32 € kg⁻¹ as the fertilisation expenses (\( C_f \)) and 160 € ha⁻¹ as the other production expenses (\( C_o \)). When developing the economic model, agricultural subsidies were excluded.

The assumption was made, in the calculation of the profitability of potato fertilization (\( R_v \), %), that the commercial yield (60% of the total) is sold at 96 € Mg⁻¹, but the rest of the yield is converted to milk or pork, the selling price of which is 0.19 and 1.28 € kg⁻¹, respectively. The cost of fertilizers is 0.32 € kg⁻¹ for K and 1.6 € kg⁻¹ for P, the cost of harvesting is 12.8 € Mg⁻¹. The feeding of animals proceeded from a balanced feed ration and the calculation of the requirement for metabolizable energy and protein was based on the requirement for purchased concentrated fodder and its cost. All input and output prices noted here were prevailing at the time of writing the papers and may be inappropriate in current socio-economic conditions. Economic models should, therefore, be continuously renewed when implemented in DSS.

### 3.6. Decision support system (I)

#### 3.6.1. Description of the study area

A GIS including database of soil properties was developed covering the fields (5000 ha) of the arable land in the Kullamaa rural municipality, which is located in western Estonia. The total area of this municipality is 224 km² of which the agricultural area makes up 22%. The average cultivation area of cereals per farm is 67 ha. The actual average productivity of cereals in the studied area, in 1992–2000, was 1.5 Mg ha⁻¹. Inadequate application of fertilisers is among the main causes of the low yield. Cereals received, in the period 1996–2000, 39 kg NPK ha⁻¹ in the form of mineral fertilisers and 3.8 Mg ha⁻¹ organic fertilisers. Mineral fertilisers were only used in 46% of the total growth area of cereals and organic fertilisers in 6.4%. The provision of location-based recommendations for fertilisation and its optimisation are essential to ensure more efficient and stable cereal production.

#### 3.6.2. The structure of a decision support system and data sources

In order to develop agro-economic models necessary for the implementation of DSS, a complex database was created using the information of scientific dissertations, publications and reports; the results of the crop variety comparison experiments; the databases of agro-meteorological stations; the data of the Animal Recording Centre (Joudluskontrolli Keskus); the databases of the institutions of nature and environmental conservation, the Statistical Office, the Land Board, the Agricultural Registers and Information Board (Põllumajanduse Registrite ja Informatsiooni Amet), and the Estonian Agricultural Research Centre. Such an up-to-date analysis of the large-scale database, covering the whole agricultural production, allowed this study to develop the agronomic and economic models of the productivity and yield quality of particular field crops as well as of the production and marketing of products of animal husbandry.

A shortcoming of computer-based DSS in agriculture is often the unavailability of required input data (Parker and Campion 1997); in order to overcome this disadvantage in the development of DSS, this study proceeded from available vector maps and databases. The aim of this approach was the feasibility of optimisation of agricultural land use at different levels, making use of the materials collected by various State agencies and research institutions. Such an approach allows implementation of the developed DSS across the whole of Estonia.
The main component of the system is the map layer of the arable fields (Figure 1 in I). The polygons of the fields were mapped by the Estonian Agricultural Registers and Information Board. The initial data for each field used in the agronomic models were soil quality points (on a 100-point scale), humus content (determined by the Tjurin method), and the content of available phosphorus and potassium (determined by the Egner-Riehm double lactate method). The calculated new agronomical values serve as a basis for the application of economic models. The new agro-economic values for each field and the compiled thematic maps or tables can be used in decision making processes. Information flow for decision makers and stakeholders is possible from output data of DSS models or directly from input data layers. Non-spatial information flow (including expert opinions) to the DSS is essential to develop agronomic and economic models and to supplement the decision making process.

There are several approaches to combine GIS with modelling (Sui 1998). In the current DSS, GIS and modelling are in a loose coupling category that integrates GIS with analytical models through the exchange of data files. Neither agronomic nor economic models are directly associated with GIS. This approach requires little investment in software development (Matthews et al. 1999). Fedra (1996) proposes an integrated framework in which GIS and modelling remain as two separate systems with the capacity for information exchange between them. The calculations based on the algorithms used in the models were made using MS Excel and the new values were then updated in GIS. The software systems MapInfo Professional and MicroStation Geographics were used in the development of the GIS.

Using GIS environment, topology analysis of the field layers and soil map polygons was performed (Figure 1 in I). The generated database with soil characteristics can provide input values for models used in DSS. A digital soil map (scale 1:10,000) was used for analysing the soils of agricultural land. The scale 1:10,000 is appropriate for decision making at the field level (Avery 1987). Digital soil maps of Estonia, covering the whole territory, as well as maps of the lime and fertiliser requirements of arable soils have been compiled. The database supplementing the digital soil map includes the following data: soil type, texture abbreviation, thickness of the epipedon, classes of stoniness, and soil quality points. As most of the data in the soil database are in a string format, the application of these data in models for generating new values is limited.

To assess the cultivation value of soils, the points of soil suitability indexes for selected field crops were also entered in the database (Figure 1 in I). The soil suitability index (0–10 points) developed for the conditions of Estonia takes into account the productivity of different soils by the main crops (Valler 1973, 1982; Kõlli 1994).

The soil quality points and the data of humus content were drawn from the databases of the Land Board. The data of soil available phosphorus and potassium were obtained from the archives of the Estonian Agricultural Research Centre. The determination of fertiliser requirements in Estonia practically stopped in the 1990s, so the results of the last nationwide determination (1985–1989) were used in this study. This enabled the evaluation of soil nutrient requirement for the entire study area and, proceeding from this, to identify the possibilities of DSS application. The State supported determination of fertiliser requirement was restarted in 2002 and the results of the current determination will be entered directly in the GIS. This serves as a solid basis for the implementation of the developed DSS for the optimisation of fertilisation throughout Estonia. Since one soil sample in both previous and current agro-chemical soil survey represents 3–5 ha, then these data are suitable for modelling and decision making at field-scale.
4. RESULTS

4.1. Changes in agricultural land use

Estonian agricultural production has, since the re-establishment of the independence in 1991, undergone a drastic decline during the transition from a heavily subsidised command economy to a free market economy. The aggregate area of arable land has decreased to 53% of the pre-1991 level, cereal production to 53%, meat production to 29% and milk production to 50%. Gross agricultural output decreased by more than twice during the first ten years of independence. The cultivation area of field crops has steadily diminished since 1990 by about 39,500 ha a year. The major decline is in the growing area of forage crops with an aggregate decrease of 485,000 ha, the area for cereals and legumes has decreased by about 130,000 ha and the growing area of potato by 28,000 ha. The only area to show an increase is that for industrial crops, up by 41,000 ha (Figure 1).

The pedo-climatic conditions necessary for the development of competitive agriculture are highly variable in Estonia, which combined with the socio-economic factors of the transition period have ensured that changes in agricultural land use in the 1990s differed significantly from region to region (Figure 1; Table 1). Arable land use has declined mostly in the rural municipalities located in regions with low fertility soils ($r = 0.63; p < 0.000$) (Figure 2). An increase in soil fertility by one quality point brings about a 2.5% decrease in the proportion of abandoned land. Although also the population of rural municipalities has decreased 7.8%, the area of agricultural land on low fertility soils in northern, eastern and south-eastern Estonia as well as around Lake Peipsi and in Hiiumaa Island has decreased 2–10 times per capita. Indeed the loss of arable land in forty-two of the rural municipalities in 1992-2001 was more than 70% (Figure 1). The anomalous +533% refers to the island of Ruhnu with an area of 11.5 km$^2$, where the size of the percentage increase bears no relation to the miniscule area involved, 10.6 ha to 67 ha.

Municipalities situated in less favoured areas (LFAs) for arable land have experienced a 59% decrease and in other regions 37%. The continued decline in arable land in 2001–2003 was halted and reversed in 2003–2005. Although the statistic of an average increase of 9% seems to give a more positive outlook there are some extremely large regional variations (Table 1).

![Figure 1. Changes in arable land (%) in Estonia's 199 rural municipalities, 1992–2001. The number in brackets for each denoted range shows the number of municipalities.](image)

<table>
<thead>
<tr>
<th>County</th>
<th>Changes in arable land, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harju</td>
<td>-53</td>
</tr>
<tr>
<td>Hiium</td>
<td>-69</td>
</tr>
<tr>
<td>Ida-Viru</td>
<td>-67</td>
</tr>
<tr>
<td>Jõgeva</td>
<td>-37</td>
</tr>
<tr>
<td>Järva</td>
<td>-23</td>
</tr>
<tr>
<td>Lääne</td>
<td>-59</td>
</tr>
<tr>
<td>Lääne-Viru</td>
<td>-30</td>
</tr>
<tr>
<td>Põlva</td>
<td>-45</td>
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<tr>
<td>Pärnu</td>
<td>-48</td>
</tr>
<tr>
<td>Rapla</td>
<td>-38</td>
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<tr>
<td>Saare</td>
<td>-54</td>
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<tr>
<td>Tartu</td>
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<tr>
<td>Valga</td>
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<td>Viljandi</td>
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<tr>
<td>Võru</td>
<td>-63</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-47</strong></td>
</tr>
</tbody>
</table>
4.2. Changes in plant nutrient balances of arable soils and the use of fertilisers

State subsidies for agriculture were sizable in the Soviet period up to 1991 at which time the average quantities of plant nutrients introduced into the soil increased at a rate of 4.5 kg N, 2.8 kg K and 0.6 kg P ha⁻¹ per year. Simultaneously, the quantities of nutrients taken up by plants and removed with the yield increased on average by 1.3 kg N, 1.0 kg K and 0.2 kg P ha⁻¹ per year. The quantities of plant nutrients N, K and P applied to the fields exceeded the amounts removed through crop harvesting by a factor of 2–2.3 (N), 1.9–2.2 (K) and 3–3.5 (P). Due to the notably positive total balance of plant nutrients (Figure 3 in II., the amounts of lactate soluble P and K increased by 1.1 mg kg⁻¹ and 0.7 mg kg⁻¹ of soil per year, respectively.

The application of both mineral and organic fertilisers that had started increase in the 1960s peaked in the 1980s. The amount of mineral nitrogen fertilisers applied per hectare of arable land was then more than 100 kg N ha⁻¹, while the respective amounts of phosphorus and potassium fertilisers were 26 kg P ha⁻¹ and 75 kg K ha⁻¹, respectively (Figure 3 in II.). The amount of applied organic fertilisers in that period was up to 12 Mg ha⁻¹. The amount of nitrogen applied with mineral and organic fertilisers has varied from 30 kg to 150 kg ha⁻¹ of which the proportion of nitrogen from mineral fertilisers makes up 3–66%.

The average amount of fertilisers applied per hectare of arable land in the period since independence in 1991, compared to the 1980s, are reductions by a factor of four for organic, six for nitrogen, twenty for phosphorous and thirty for potassium. During this period the total balance of K and P has become negative as a consequence of inadequate fertilisation, whereas in the case of N, the total inputs have equalled the output occurring with crop harvesting (Figure 3 in II). Although the average amount of manure used in 2001–2003 was only 2.8 Mg ha⁻¹, the proportion of total mineral inputs from manure were 53% for K, 45% for P and 22% for N. The use mineral fertilisers has slightly increased since the mid-1990s but the applied amounts are still extremely low – 34 kg N ha⁻¹, 3.5 kg P ha⁻¹, and 10.4 kg K ha⁻¹.

The application of mineral fertilisers in the current economic situation is only within the spending power of the richer producers and farms situated in areas with more favourable pedo-climatic conditions (II.). There is a strong correlation between the application of mineral fertilisers and soil quality (r = 0.81; p < 0.000). A decrease in soil fertility reduces the amount of mineral fertilisers used by 2.85 kg NPK per one soil quality point. Finances for fertilisers, due to limited economic resources, are below 20 € ha⁻¹ in many agricultural enterprises, although 1 € invested in fertilisers will increase total plant production by 5.44 €.

It is necessary to take into account that plants utilize only a certain amount of total input of nutrient balances. An active plant nutrient balance for arable soils (Figure 4 in II.) is based on the amounts of fertilisers introduced into the soil and from all other balance input, as well as from the coefficients of nutrients utilization by plants. The active balance shows that at present the largest deficit is of P (68%) followed by K (57%) and N (34%). Such a balance allows the estimation of the degree to which formation of the yield occurs at the expense of soil resources. The difference between the amounts of plant available inputs and the amounts removed with the yield is negative: -24.5 kg N, -6.5 kg P and -26.2 kg K ha⁻¹.

Agricultural producers in the current economic situation 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 (Figure 5 in II.). 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 (Table 1 in III.). The application of mineral fertilisers for oilseed rape (66 kg N ha⁻¹, 10 kg P and 30 kg K ha⁻¹) has been more intensive compared to cereals.

4.3. Crop productivity and yield gap

The many-year average yields of winter cereals in the crop variety comparison tests which are provisionally equalled with yield potential are 3.5 Mg ha⁻¹ (Figure 1 in III.). In unfavourable years, with a probability of one year out of ten (10%), the yield of rye and winter wheat can be less than 2 Mg ha⁻¹. However, in favourable years the yield of winter cereals can be 5.5 Mg ha⁻¹. According to the results of the crop variety comparison tests, the yield of spring cereals has been somewhat higher compared with winter cereals. The average yield potential of spring wheat is more than 4 Mg ha⁻¹, the yield of
oats 4.5 Mg ha\(^{-1}\) and the yield of the barley up to 5.0 Mg ha\(^{-1}\). A maximum yield among the studied varieties, obtained in the crop variety comparison tests, was 6.5 Mg ha\(^{-1}\) for spring wheat, 7.5 Mg ha\(^{-1}\) for oats and more than 8.0 Mg ha\(^{-1}\) for barley. At the same time, in the case of an extremely dry summer the yield of spring cereals can be only 1 Mg ha\(^{-1}\). The average yield of oilseed rape is 2.0 Mg ha\(^{-1}\) and the maximum yield has reached 3–3.5 Mg ha\(^{-1}\); however, the risk of yield failure is relatively high.

The many-year national average grain yields have been approximately 2 Mg ha\(^{-1}\), and 1.2 Mg ha\(^{-1}\) for oilseed rape (Figure 1 in III). Taking into account the existing level of production and weighing it against the level estimated from the crop variety comparison tests, it appears that approximately 40–50% of the real yield potential of cereals is realised at present. In the case of oilseed rape the utilisation of the yield potential is 60–65%. The yield gap between yield potential and the national average is especially large in favourable growing years. In the instance of unsuitable climatic conditions the yield gap is relatively small.

Cereal cultivation is, due to natural factors, has an extremely high risk probability, as pedo-climatic conditions affect not only the yield but also its quality (Figure 1 in III). The yield of cereals depends mainly on soil fertility, climatic conditions and the use of fertilisers (Figure 2 in III). An increase in the yield of cereals at the expense of soil fertility is about 36–40 kg per point of soil quality. The yield of cereals can, depending on the soil quality, increase on average 10–99% at the expense of fertilisers. The yield of cereals is in extent of 50–60% determined by the pedo-climatic conditions and the proportion of fertilisers in yield formation is lower.

The yield of wheat, as an average of the specialised FADN grain farms, in 2000–2003 was 2.3 Mg ha\(^{-1}\), the yield of barley 2.0, the yield of oats 1.9 and the yield of rape 1.7 (III). This productivity in comparison against the national average was 15–20% higher for cereals and 6% higher for oilseed rape. The variability of the yield among different farms was extremely high (coefficient of variation 31–37%). The yield of cereals and oilseed rape depends on the level of total and specific costs (\(r = 0.32–0.39; p < 0.01\)). The lack of farm-specific data of the quality of arable land in the FADN database does not allow any assessment of the effect of soil fertility on the yield level. Whereas the maximum yield was 5.6 Mg ha\(^{-1}\) for wheat, 5.1 for barley and 3.2 for oilseed rape, only 10% of the producers achieved yields of these crops greater than 3.8, 3.5 and 2.3 Mg ha\(^{-1}\), respectively. Bigger yields ensures a profit increase for producers (\(r = 0.33–0.37; p < 0.01\)).

4.4. Effectiveness of mineral fertilisers

Barley

The effectiveness of fertilisation depends to a large extent, besides soil properties, on meteorological conditions. On the basis of all field trials conducted to date, it can be calculated that the application of the \(N_{50}\) fertiliser norm for intensive barley varieties on automorphic soils, with soil humus content ranging between 2% and 4%, yield increase is 15–18 kg kg\(^{-1}\) of barley (Figure 4 in I). The lower the humus content of soils, the higher is the effect of nitrogen fertilizers. 25–30 kg of grain can be obtained with a probability of 10–20%, in highly favourable years, at the expense of 1 kg of nitrogen. However, on gleyic and gley soils, which are richer in humus, this amount of nitrogen can lead to lodging of the crop and a yield decrease in one to two years out of ten.

The many-year average (probability 50%) effectiveness of mineral phosphorus (\(P_{50}\)) varies from 0–12 kg kg\(^{-1}\) P\(^{-1}\) depending on the soil P status (Figure 2). In favourable years as much as 10–26 kg of grain can be obtained at the expense of 1 kg of P. On soils with available P content more than 95 mg kg\(^{-1}\) is the probability to obtain yield increase less than 50%. The many-year average effectiveness of mineral potassium (\(K_{50}\)) for barley can be up to 7 kg kg\(^{-1}\) K\(^{-1}\) (Figure 3). On soils with very high K requirement the average effectiveness is in seven years out of ten over 4 kg kg\(^{-1}\) K\(^{-1}\).

![Figure 2. Probability (P, %) of the effectiveness (kg kg\(^{-1}\) P\(^{-1}\)) of the \(P_{50}\) fertiliser norm depending on soil lactate soluble P content (mg P kg\(^{-1}\)).](image-url)
The evaluation of efficiency of barley fertilisation should also consider, beside pedo-climatic risks, economic criteria such as the cost of fertilisation and the price of the yield. The profitable effectiveness of mineral N, at which fertilisation costs are completely covered by additional income, varies from 4–15 kg kg\(^{-1}\) N\(^{-1}\) (Figure 4), however, to ensure profitability of fertilisation at current fertiliser (0.6 € kg\(^{-1}\) N\(^{-1}\)) and barley prices (100 € Mg\(^{-1}\)) the average effectiveness must be higher than 7.4 kg kg\(^{-1}\) N\(^{-1}\).

Potato

The higher effectiveness is achieved when crop nutrient supply is balanced. Very important factors influencing the effectiveness of nitrogen fertilizers, for potato, are the PK fertilizer background and the soil’s requirement for phosphorus and potassium fertilizers. Non-application of PK fertilizers results in a significantly lower effectiveness of nitrogen fertilizers and involves a higher risk on humus-rich soils (Figure 5). When phosphorus and potassium fertilizers are not used and soil humus content is 2–3% the average effectiveness of the N\(_{60}\) fertilizer norm is 40–50 kg kg\(^{-1}\) N\(^{-1}\). In highly favourable conditions (probability 10%) the average effectiveness of this fertilizer norm can reach 80–90 kg kg\(^{-1}\) N\(^{-1}\), while in unfavourable years (probability 90%) it can remain below 15 kg kg\(^{-1}\) N\(^{-1}\). Application of PK fertilizers increases the efficiency of N\(_{60}\) for potato by 28 kg kg\(^{-1}\) N\(^{-1}\).

The average effectiveness of fertilizer application, using relatively low phosphorus fertilizer norms (P\(_{25}\)) with the use of mineral nitrogen, on soils with high and very high fertilizer requirement is 120–140 kg of tubers per kg P (Figure 2 in IV). The effectiveness of P\(_{25}\) varies from four to seven fold in different years. On soils with a moderate amount of available phosphorus, the average effectiveness of the P\(_{25}\) fertilizer norm is about 90 kg kg\(^{-1}\) P\(^{-1}\), while on soils with low fertilizer requirement the average expected yield increase is 56 kg of tubers per kg P. When the content of soil lactate soluble phosphorus is 100 mg kg\(^{-1}\), yield increase with the use of phosphorus fertilizers can be expected only in three to five years out of ten. The use of phosphorus fertilizers, despite their relatively high...
expense, is wholly justified because average fertilization profitability on soils with moderate phosphorus supply is 60–120% depending on the possibilities of the utilization and realization of yield increase.

The average effectiveness of the $K_{0}$ fertilizer norm used for potato, against the background of nitrogen and phosphorus fertilizers, on soils with low and very low content of available potassium, is 75–100 kg kg⁻¹ K⁻¹ as an average of many years; however, it can even be as high as 140–170 kg kg⁻¹ K⁻¹ in one favourable year out of ten (Figure 1 in IV). On soils with moderate and high potassium supply the average effectiveness of this fertilizer norm is 30–50 kg kg⁻¹ K⁻¹. On soils with still higher potassium content the probability of yield increase at the expense of applied potassium is moderately low, 30–60%. As potassium fertilizers increase significantly the yield of potato and are relatively cheap, their application at rate $K_{0}$ is consequently profitable and involves small economic risk on potassium poor soils. The economic risk is, however, particularly high on soils where the content of available potassium is over 150 mg kg⁻¹ (Figure 1 in IV).

4.5. Decision support system for agricultural land use and fertilisation optimisation: a case study on barley production in Kullamaa rural municipality

**Soil resources**
The soils of the study area are dominated by different gleysoils (43.5%) among which the proportion of Mollic Gleysols is the largest (Table 1 in I). The share of automorphic and gleyic Calcaric Cambisols is also substantial. Peat soils account for 8.3% of arable land in the area. Soil quality ranges, in different fields, between 22–52 points with weighted average 37 points. The fields with soil humus content less than 3% account for only 8.6% of arable land, while humus-poor soils (humus content less than 2%) are absent (Table 2 in I). Less than a quarter of all arable land is characterised by soils with high phosphorus and potassium content. The soils with a high cultivation value for barley accounts for 28.7% of arable land (Table 3 in I).

**Effective norms of mineral fertilisers**
Field-specific agronomically effective fertiliser norms for barley, ensuring a maximum yield, depend on soil fertiliser requirement and vary in very large limits in the region with maximum values up to 103 kg ha⁻¹ for nitrogen, and 27 kg ha⁻¹ and 60 kg ha⁻¹ for phosphorus and potassium, respectively. Effective fertiliser rates decline with increasing soil NPK supply. As there is a strong correlation between total soil nitrogen content and soil humus content ($R^{2} = 0.97; se = 0.019; p < 0.000$), it is possible to estimate the need for nitrogen fertiliser proceeding from soil humus content (Roostalu et al. 2003). The agronomically and economically effective norms of nitrogen fertiliser were calculated, for each field, on the basis of soil humus content (Figure 2 in I). In order to generate such an equation, previously effective fertiliser norms were determined for several soil nutrient supply levels. A similar approach enabled the calculation of effective P and K fertiliser rates for each field on the basis of soil lactate soluble P and K content, respectively.

Although the use of agronomically effective fertiliser norms ensures a maximum yield, this practice is not economically justified, as at a certain point the profit gained from an additional amount of fertiliser is lower than the extra costs. Compared with the agronomically effective fertiliser norms, the economically effective fertiliser norms, which guarantee a maximum profit in barley production, are 23% lower for N, 12% lower for K and as much as 59% lower for P. Economically effective N norms range from 50 to 60 kg ha⁻¹ on 67.1% of agricultural land (Figure 3 in I). It is not economically reasonable to use nitrogen fertilisers for barley on 18.7% of the land.

**Profitability of barley cultivation**
The yield of barley and hence the profitability of barley production depend on soil fertility, weather conditions during growth, soil fertiliser requirement, amount of the fertilisers used and their cost and on the price of the crop. The profit depends as well on the possibilities of converting grain yield into the output of animal production and its price and also on other production expenses and factors. The simulated barley yield obtained at the expense of soil fertility remains, with non-application of fertilisers, in the range of 0.7 to 1.8 Mg ha⁻¹ in the study area. Depending on climatic conditions, the barley yield without fertilisation varies more when soil is less fertile. The average barley yield on poor soils, estimated at less than 30 quality points, is only 1 Mg ha⁻¹, while in unfavourable years the crop may practically fail altogether. With the use of economically effective amounts of NPK fertilisers, the barley yield in the study area ranges from 1.0 to 4.3 Mg ha⁻¹. The average yield of the fertilised variant is 2.6 Mg ha⁻¹. Depending on soil properties, the profitability of barley cultivation varied in a very broad range in the study area (Figure 5 in I).
production in the current market situation is not economically profitable on 28.3% of agricultural land. On the other hand, the profitability of barley production on 35.3% of agricultural land is higher than 20%.

The instability of the prices for agricultural products is the main factor, which influences the profitability of agriculture. When barley is sold at low prices (90 € Mg⁻¹) the proportion of profitable land would be 28%, but with a 10 € increase in the price, 59% of arable land would yield profit (Figure 6 in I). However, even at high selling prices, the cultivation of barley would be unprofitable in some fields. The selling price of barley produced without mineral fertilisers must be considerably higher in order to gain a profit equal to that gained with the application of economically effective fertiliser norms. The selling price of non-fertilised barley must be more than 1.5 times higher in order to achieve profitability comparable to that gained from the production of fertilised barley.

The conversion of barley into animal products, as opposed to direct sales, is possible on the assessment of the economic suitability of agricultural land on the basis of the profit gained from, for example, pork or milk production. To gain profit from at least 70% of arable land in the study area, the selling price of barley must be higher than 106 € Mg⁻¹. In order to gain the same profit from pork production, the price of pork must be higher than 130 € 100 kg⁻¹ and in milk production the price of milk must be higher than 181 € Mg⁻¹ (Figure 6 in I).

5. DISCUSSION

5.1. Changes in agricultural land use

Arable land decreased in Estonia during the transition period from the Soviet period to the free market economy by 47% (II). This was the most drastic change in all Europe, and the decrease in Estonia’s arable land was higher by a factor of 3.9 compared to other post-Soviet European countries (12%). The area of arable land per capita has decreased continuously worldwide, from 0.41 ha in 1960 to 0.22 ha in 2002 (Faostat 2006). The forecast is that by the year 2050 the average area of arable land per person will be 0.15 ha (Kutter et al. 1997). In 2003 the proportion of land per capita in Estonia was 0.41 ha for arable land and 0.63 ha for agricultural land. These proportions are greater than in EU15 countries, by factors of 2.2 and 1.7 respectively. Nevertheless, during the last decade Estonia was unable to ensure agricultural self-sufficiency (III), which considering its bio-physical conditions, resources and historical experience, the nation should be able to guarantee. The drastic decline in agricultural land use (II) and in livestock production has caused since 1997 a negative agricultural self-sufficiency (Rask and Rask 2004) and Estonia is now dependent on food imports. Rask and Rask (2004) also found a similar tendency in Latvia but not in Lithuania where self-sufficiency was maintained during transition period. This contrast can be explained by the higher level of agricultural subsidies in Lithuania (Trzeciak-Duval 1999). The low agricultural self-sufficiency ratio in most transitional CEECs is confirmed also by Balcombe et al. (1999) and Csaki (2000). A further decline in agricultural land use will endanger not only national food security but also sustainability rural life as well as causing a decrease in landscape diversity (Sepp and Hiiemäe 2003). Simultaneously, changes in land use have resulted in the decline of soil erosion (Reintam et al. 2001).

The end of the decline in agricultural land use in 2004–2005 (Table 1) can partly be explained by the implementation of the EU CAP and the related increase in subsidies. Whereas all agricultural subsidies were around 30 € ha⁻¹ in 2003, the application of CAP schemes increased the level of subsidies by a factor of three to four. To prevent further abandonment of agricultural land in Estonia, support for LFAs was implemented in 2004. The fact that EU CAP payments, area and production quotas for the ten new EU member states were fixed according to historical production data (which were generally based on the 1997–2001 period of reductions in
consumption and self-sufficiency levels) will cause continued food import dependency for Estonia and sub-optimum use of domestic productive agricultural resources (Rask and Rask 2004). As the agricultural land use is currently determined by EU CAP no significant re-exploitation of abandoned land for food production can be expected in the near future and Van Meijl et al. (2006) have projected no drastic decrease in agricultural land for the EU25 for the next thirty years. Bush (2006) argued that increasing biofuel production as a result of both increasing energy demand and climate policies takes up a significant area of land in many scenarios and prevents substantial abandonment of agricultural land.

This is the first time that changes in arable land during the transition period were analysed at the level of Estonia’s rural municipalities. The regional differences in the changes are determined mainly by local bio-physical disadvantages like soil quality (II). The greater decrease in arable land in marginal districts of Estonia is also noted by Peterson and Aunap (1998). Highly subsidised production in the Soviet period preserved agricultural land use even in marginal areas. The loss of subsidies at the beginning of the transition period (Trzeciak-Duval 1999) highlighted the importance of pedo-climatic conditions in the formation of the economic viability of agricultural production. The Europeanization of agricultural policy has stabilised the situation in rural areas and relieved the impact of bio-physical diversity on the profitability of agriculture. The profitability of agriculture is largely affected by increased subsidies, especially in LFAs and thus regional specialities should be considered as much as possible by the development of agricultural policy. Rapid and regionally variable changes in the transition period raised the need for spatial DSS for land use planning for currently used and abandoned agricultural land.

5.2. Plant nutrient balances of arable soils

While earlier studies (Piho 1976; Raudväli 1985b; Kärblane and Kevvai 1988; Kärblane et al. 2002) have reported plant nutrient balances of Estonian arable soils for single years then the current study covers for the first time a long-term period (1939–2003). This approach enables the evaluation of some aspects of the sustainability of agricultural land use and soil management through the transition from the Soviet era to the open market economy. Significantly positive NPK soil balances in the 1970s and 1980s have improved the nutrient supply of arable soils (II). The productivity of field crops and the consequent amounts of nutrients removed from the soil did not increase proportionately with the increase in the input. Nutrient surplus can be explained by the low efficiency of fertilisers in the collective farms and state farms of that time (Roostalu et al. 2001) 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. Salo et al. (2006) showed that the highest N leaching losses are not usually caused by positive N balances, but rather due to poor management practices like bare fallow or application of slurry to the frozen soil.

Soil nutrient balances, in 1990s, became negative due to the sharp decrease in fertiliser application (II). The emission of pollutants to the environment has decreased and the general state of the environment has improved. Tamm et al. (2003) have argued that reasons for low intensity agriculture are found from economic conditions in transitional period rather than any understanding of the environmental benefits gained from ecological farming. Despite the fact that it is complicated to establish straightforward relationships between N and P surplus and environmental impact (Öhborn et al. 2003) several studies have found decreased nutrients runoff in 1990s (Mander et al. 2000; Ital et al. 2005). Stålnacke et al. (2004) concluded that large reduction in nutrient inputs to soil does not necessarily induce an immediate decrease in river NP concentrations, especially in large-scale catchments. The total nitrogen and phosphorus load to Lake Vörtsjärv, which is the biggest internal lake in Estonia, has decreased by 55% and 31% respectively from 1990–1992 to 1998–2000 (Jarvet 2003). The rate of fertilisation in small agricultural sub-catchments is the most significant factor affecting nitrogen runoff but in larger mosaic catchments land use pattern is more important (Mander et al. 2000). The nitrogen losses in catchments scale is strongly correlated with the proportion of arable land (Mander et al. 2000; Jansons et al. 2003) and land use changes are the main reason beside input reduction for the significant reduction of N losses (Kull et al. 2005). Agricultural area has decreased to 21% of all land in 2001. This is 2.2 times lower than the average for the EU25 countries. There are only fifteen rural municipalities in Estonia where the area of agricultural land makes up more than 40% of the whole area, and most of them are located in central Estonia within the Nitrate Vulnerable Zone. Agricultural diffuse and point pollution can, despite negative soil nutrient balances at the national scale in Estonia, potentially endanger water ecosystems in the case of inappropriate nutrient management in some
regions. Nutrient surpluses are often found in areas with high livestock density (Jansons et al. 2002; Gömann et al. 2005).

At present crop production takes place largely at the expense of the soil resources created by farmers in the 1970s and 1980s (II, III). Removal of nutrients from the soil cannot continue indefinitely without depleting the productivity of the soil; nutrients must be replaced. There is clear evidence that negative soil nutrient balances have already deteriorated the status of plant available K and P of arable soils in several post-Soviet countries (Cermak and Budnakova 2005; Karklins and Lipenite 2005; Nikolova 2005). According to the agrochemical survey in Estonia, the share of arable soils characterized by K deficiency (low and very low supply level) increased from 43% in 1984–1989 to 47% in 2000–2005. At present, it is difficult to determine actual changes in soil nutrient reserves at the national level because of the mismatched surveys for 1984–1989 (1.1 million ha) and 2000–2005 (170,439 ha). A comparison of changes in soil nutrient supply levels is also complicated (i) due to the sharp decrease in arable land, especially in areas with low soil fertility; and (ii) due to the regional allocation of soil sampling in 2000–2005 to the areas where fertilisation was more intensive in the 1990s. In order to obtain reliable data of changes in soil fertility, resulting from the negative plant nutrient balances in the last decade, the national agrochemical survey of arable soils should be completed.

Negative nutrient balances and sub-optimal nutrient inputs to the soil (II, III) do not endanger only the fertility and agronomic value of agricultural land but also limits crop productivity and causes inefficient use of pedoclimatic resources. According to the last nationwide agro-chemical soil survey the content of soil lactate soluble potassium of Estonian arable land is low for 43.4%, moderate for 42.6% and high for 14.0% of soils. The content of lactate soluble phosphorus is very low or low for 28.9%, moderate for 46.8% and high or very high for 24.3% of soils (Järvan et al. 1996). This supply distribution shows that on the most of arable land the use of external inputs is crucial to obtain competitive yields and to maintain or achieve optimal soil nutrient status. The conclusion that can be drawn from the results of all the fertilisation experiments conducted in Estonia until now is that on highly phosphorus-poor soils the content of available P decreases in the case of non-use of fertilisers during the first crop rotation cycle. In order to avoid such a decline, an average fertilizer amount should be no less than 10–15 kg P ha⁻¹ (Piho 1973; Kårblane 1978).

In Estonia, however, applied amounts are significantly lower, especially for forage crops (II). The limit norm of potassium should be 40–60 kg K ha⁻¹. Applications of smaller amounts will lead to soil becoming impoverished in regard to lactate soluble K (Kevvai et al. 1985; Kårblane 1985). The depletion of soil P and K may become critical especially in organic systems (Watson et al. 2002; Bengtsson et al. 2003; Öborn et al. 2005). Negative PK balances in Estonia are evident especially for grasslands (II) 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.

The main objective of current EU agri-environmental policy is to achieve less intensive production (Kleijn and Sutherland 2003; Zalidis et al. 2004). For this purpose, the balances of N and P at the field (Tunney et al. 2003) or at the farm level (Brouwer 1998) are employed in Europe. The implementation of EU agri-environmental policy has partially ignored the differences in production intensities between old and new member states and do not induce avoidance of soil degradation due to the negative nutrient balances in CEECs. Applied environmental and agricultural policy schemes in Estonia set only the upper limits for nitrogen input to the soil but do not include any requirement of balance calculations. Consequently applied measures are inefficient to prevent the threat to soil fertility arising from the consistently negative nutrient balances in Estonia. The negative plant nutrient balances of arable soils at the national level in Estonia indicates the need to also consider the nutrient balances on the regional, farm or field scale to reduce soil degradation.

5.3. Yield potential and its realisation

The agronomic efficiency of crop production determines the economic viability of individual farms and influences food supply at the national level; this is important from the viewpoint of both local and global food demand (Dobermann and Cassman 2002). The low realisation of yield potential of cereals in Estonia can be explained by the inadequate use of fertilisers (II, III). More intensive fertilisation of oilseed rape has ensured much higher realisation of the yield potential compared to cereals in the current production conditions. At the same time, average fertiliser rates for oilseed rape are environmentally friendly and in concordance with legal restrictions. Actual yield level is limited mostly by low input of plant
available nutrients to the soil and is dependent on soil nutrient reserves (II). As the average grain deficit for 2000–2003 was 25%, then to compensate for this, the national average yield of cereals must increase from 2.0 up to 2.5 Mg ha⁻¹. Considering the real yield potential and existing yield gap, this would be feasible, but only if producers are economically motivated to intensify production and optimise inputs to some degree.

The experimental yield level varies by a factor of three to four depending on the climatic conditions (III) and therefore the involvement of risk analysis in the farming decision making process is crucial. Climatic risks can be relieved but not eliminated by optimal use of fertilisers while the variation in yields, related to climatic conditions, is two to four times higher compared with yield increase at the expense of fertilisation (III). Assessment of the realization of yield potential should be adjusted to local conditions while optimal yield level depends on the soil fertility. Yield risk analysis is especially useful when it is carried out on field level (Popp et al. 2005) and thereby joining the spatial information with yield probabilities provides solid basis for knowledge-based decision making.

Agronomic efficiency in FADN farms is somewhat higher compared with the national average but grain yield differs to a great extent between farms (III). The high variability of the yields among different farms can be partly explained by the level of production costs. The producers who use more inputs usually achieve higher grain yields. The analysis of FADN farms indicates a positive correlation between input level, yield and profit but despite that the suboptimal use of fertilisers has not significantly changed. Higher grain yields in Estonian grain farms are related to the intensity of specific costs (Vasiliev et al. 2003) and simultaneously to better economic performance (Matvejev 2007). This reveals that the high yield gap due to the low-input production practices also causes the competitiveness of grain producers to deteriorate. The strong positive relation between the application of mineral fertilizers and soil quality (II) reveals that dominating low-input crop husbandry is induced by socio-economic conditions and by political pressure and not by agronomic knowledge. The higher efficiency of fertilisers can be expected on soils with sub-optimal nutrient supply and vice versa (Blake et al. 1999; Mengel et al. 2006) and low fertility soils are unable to provide the competitive productivity without external inputs (Cassman 1999). Kirchmann and Thordvaldsen (2000) argued that the driving forces behind organic agriculture are beliefs originating from a philosophy of life and not scientific thinking. In order to narrow the yield gap and to improve agricultural self-sufficiency, resource use efficiency, and profitability in an environmentally friendly way, the fertiliser and other input optimisation should be based more on scientific knowledge.

5.4. Fertiliser optimisation

Agronomically effective fertiliser norms ensuring a maximum yield depend largely on soil fertiliser requirement (I). Effective fertiliser rates are in reverse relationships with increasing soil NPK supply and depend on climatic conditions. On Estonia’s automorphic soils where the humus content is 2%, the many-year average agronomically effective amount of nitrogen fertiliser for modern barley varieties is 103 kg N ha⁻¹ but in single years this amount can exceed 200 kg N ha⁻¹, while in droughty years it can be less than 70 kg N ha⁻¹ (Roostalu et al. 2003). According to Piho (1973) the agronomically effective fertiliser rate for potato may vary more than two to three times depending on the weather conditions. In fertiliser optimization the balance must be reached between the nutrients requirements of crops which determine agronomically effective rates and the farming socio-economic conditions which determine economically effective rates. The high variability of effective fertiliser rates is proved in the example of the Rothamsted experiment where the economic optimum rate of N for winter wheat in 1990–2001 varied from 174–240 kg N ha⁻¹ (Olfs et al. 2005). Therefore, even in the case of soil-specific fertiliser optimisation the climatic risk of miss-matching the crop nutrient demand and availability remains relatively high. Overestimation of effective N rate with high input (over 100 kg N ha⁻¹) can cause environmental pollution and is related to economic loss. In order to minimise losses in intensive systems, a split application (Conry 1995) and plant analysis (Rice et al. 1995) are suggested. Richards et al. (1995) concluded on the example of seven field trials with winter barley that application of fertilizer N up to the economic optimum rate could be regarded as consistent with the objective of minimising the risk of nitrate leaching per hectare and per yield unit. An agronomically effective norm depends also on pre-crop and its fertilisation (Piho 1973), on soil tillage (Mengel et al. 2006), and on soil compaction (Reintam et al. 2005).

Efficiency of fertilisers is crop-specific and depends on the soil fertiliser requirement and climatic conditions (I, IV). As the fertiliser efficiency depends primarily on the soil nutrient status the need for at least
field-specific fertiliser recommendation is crucial for sustainable agriculture. The higher soil nutrient supply level means lower efficiency and vice versa. The average effectiveness of $N_{60}$ for spring barley decreases by 1.7 kg and for potato by 7.5 kg with increasing soil humus content by 1%. Piho (1973) found decreasing effectiveness of $N_{60}$ per 1% of humus from 12% to 16%. The variance of average effectiveness even of relatively small rates of mineral fertilisers ($N_{60}$, $P_{26}$, and $K_{50}$) is very high (I, IV). The importance of developed fertiliser effectiveness models is the capability to consider the impact of the climatic risks through probability. Previously developed models by Piho (1975) were static and excluded risk analysis in fertiliser optimisation. Roostalu and Makke (1994) concluded that the average efficiency of agronomically effective amount of N fertiliser for barley varies more than six times in different years in Estonian conditions. Piho (1973) found average effectiveness of $N_{60}$ for barley 8.6 (1.6–16.0) kg kg$^{-1}$ $N$ and for potato 30 (-21–56) kg kg$^{-1}$ $N$, of $P_{26}$, for barley 8.9 (6–16) kg kg$^{-1}$ $P$, and of $K_{50}$, 4.2 (1.4–11.8) kg kg$^{-1}$ $K$. Research by Yadav (2003) reported also high inter-annual differences in fertiliser effectiveness for wheat: N 5.0–13.1 kg, of P 15.2–61.3 kg, and K 4.9–22.8 kg grain per kg nutrient. Mengel et al. (2006) showed N efficiency for barley from 0 to 30.3 kg kg$^{-1}$ $N$ depending on the experimental site and tillage method. They explained zero efficiency by the soil in the intensity of interlayer NH$_4^+$ which presumably contributed to crop nutrition. The high variability of efficiency is largely determined by water availability to crops, and Hatfield and Prueger (2004) suggested that integrating soil water supply and soil organic matter with N management will increase the efficiency of N use and reduce the environmental impact of agriculture. A study on Swedish clay soils showed that yields of cereals in organic systems were 15–50% lower than in conventional systems, leading to a less efficient use of N in organic cropping system; in order to improve N use efficiency the synchronicity of N mineralization from green manures and N uptake by the crop should increased (Aronsson et al. 2007). Fertiliser effect on the yield increase is also crop-specific. At the fertiliser rate $N_{60}$, $P_{26}$, $K_{50}$, the proportional effect of N in the yield increase for barley is 53% and for potato only 26%, while the share of K is 22% and 42%, respectively (Piho 1975).

Crop response to K fertilisers is usually greater in dry than in wet vegetation seasons (Kuchenbuch et al. 1986) and Piho (1973) found that a higher than average effectiveness of potassium fertilizers can be expected in a relatively cool summer. In the case of a one-sided use of potassium fertilisers, but also against the background of manure, their effectiveness remains considerably lower. Blake et al. (1999) explained this due to the fact that farmyard manure was the preferred source of K and concluded that the effectiveness of K fertilisers, based on three long-term experiments in UK, Poland and Germany, is greatly reduced by deficiencies of N, P and Mg.

Higher efficiency is guaranteed in the case of balanced fertilisation (IV) but the optimum combination of nutrients depends not only on their separate and combined contributions to plant yield but also on their relative prices. Therefore the estimation of output prices received for crop yield, and the cost of applied nutrients is as crucial as that of the pedoclimatic risks (I, IV). To achieve high efficiency of applied inputs and minimise environmental pollution in addition to balanced fertilisation, more attention has also to be given to integrated cultivation and plant protection measures (Bučienė et al. 2003).

In this study the average efficiency of fertilisers must be analysed in the context of relatively small input intensity because the efficiency of fertiliser generally decreases with increasing application rate. Johnson and Raun (2002) showed that the efficiency of N for winter wheat, averaged over a thirty year period, was 49% at the rate 22 kg ha$^{-1}$ and decreased to 34% at the rate 112 kg ha$^{-1}$. Piho et al. (1976) found that on the background of $N_{60}$, $P_{26}$, $K_{50}$ the efficiency of an additional amount of $N_{30}$, $P_{14}$, $K_{25}$ compared with the efficiency of first fertiliser rate rose by a factor of 5.3 for barley, 3.1 for winter cereals and fell by 1.6 for potato. A long-term experiment, 1976–2005, in Estonia showed that on the background of $N_{60}$ an additional fertiliser rate $N_{60}$ increased significantly the yield of mono-crop barley in only 40% of the years (Häusler and Hannolainen 2006). Chloupek et al. (2004) reported the highest yield increase per 1 kg of nutrients (NPK) from mineral fertilisers in wheat and potato at the level of application 70–120 kg ha$^{-1}$ nutrients.

The development of crop response models to fertilisers was based on the large-scale database of agronomic experiments and fertiliser optimisation that is presented for spring barley (I). Since the last locally developed crop response models originated from the 1970s there is the crucial need to provide improved models applying the possibilities of modern information technology. The commonly used fertiliser recommendation systems in Estonia (Kevvai and Kärblane 1996; Rooma and Toomsoo 2002;
Kanger et al. 2003) do not take into account the economic criteria but this shortcoming is excluded in the models developed in this study. The models for the average effectiveness of mineral fertilisers for barley (I) and potato (IV) included for the first time a risk analysis capability. Improved agronomic models operating in spatial and temporal scales are forming a basis for knowledge-based DSS.

5.5. Development of agro-economic spatial DSS: analysis of the case study

The application of crop response models made it possible to determine effective mineral NPK norms for each arable field (I). The field-specific recommendations are provided for yield and profit maximization. While the agronomically effective N norms for barley reaches over 100 kg ha\(^{-1}\) then the economically effective N norms are 50–60 kg ha\(^{-1}\) in most of the area. As the soils of the study area are largely humus-rich (I), then the effectiveness of nitrogen fertilisers and their optimal amounts remain relatively low.

Economic constraints due to the high fertiliser price is most important for P and this can lead to suboptimal use of P for maintaining soil fertility and the reduction of the efficiency of other inputs like N fertilisers. Applications of N, for barley, are uneconomical on a quarter of the arable land in the study area (I). This shows clearly that field-specific fertiliser optimisation compared to uniform fertiliser application can help farmers to avoid economic loss and environmental pollution. An analysis by Gareau (2004) in USA proved that the choice of plant nutrient management can significantly influence farm profitability. Brown et al. (2005) reported that the application of DSS to optimise N fertilisation of British grasslands enables the reduction of nitrate leaching by up to 46% and fertilisers by 33%, without sacrificing herbage yield. Sacco et al. (2003) also reach the conclusion that field-specific fertiliser recommendations will increase the profit and the nutrient use efficiency as well as reducing negative impacts on the environment.

The fertiliser norms found on the basis of soil fertiliser requirement for barley production in a particular region are also consistent with environmental and legislative restrictions. The soil database makes it possible to attain additional information to supplement field-specific fertilizer recommendations with environmental criteria. Application of such an approach would be especially useful in areas with Nitrate Vulnerable Zones, which are located in regions with intensive agriculture in Estonia. There is an increasing need to improve existing fertiliser recommendation systems to relate production to environmental impact (Brown et al. 2005) and this is crucial also for further development of our DSS. The study by Kersebaum et al. (2006) in Germany demonstrated that 75% of agri-environmental measures were placed in areas with low impact on groundwater and surface waters and therefore, the efficiency of the agri-environmental measures concerning water protection was moderate. This indicates the need to adopt more precise spatial information to manage environmental risks in agriculture and a developed DSS provides a solid basis for this purpose.

As the efficiency of fertilisers is related with high inter-annual variability (I, IV), it is essential to embed risk analysis in the decision making process. The application of probability models enables the estimation of the degree of economic risk. In our case study the probability of gaining an economic profit with the application of the N\(_{avg}\) fertiliser norm was higher than 80% (i.e. in eight years out of ten) in 79.6% of the studied area. In the remaining area, however, the agro-economic risk with the use of this particular N fertiliser norm was very high due to pedo-climatic conditions. The provision of spatial recommendations is crucial, as in some fields the probability of profitable fertilisation is minimal even at low N rates.

The simulated barley yield obtained at the expense of soil fertility remains, with non-application of fertilisers, below 1.8 Mg ha\(^{-1}\) in the study area but with the use of economically effective amounts of NPK fertilisers the average yield is 2.6 Mg ha\(^{-1}\) (I). The actual farm yield of cereals in the study region is 42% lower compared to fertilised variant. Thus the proposed DSS provides prerequisites for optimisation of barley fertilisation and for increasing the effectiveness of crop production in general.

Field-specific profitability of barley production (I) provides information for agricultural land use planning. Visualisation of the results by means of thematic maps enables the clear presentation of spatial variability in the profitability of barley production at the level of the field, farm or region. It is possible, on this basis, to up-scale the modelling results from field-level to regional level (Saarikko 2000; Tan and Shibasaki 2003). The compiled thematic maps can be used in field-specific decision making and in the allocation of barley production. Farmers can use field-specific profitability data with other criteria for crop rotation planning and for
strategic decisions but presented DSS do not make decisions, rather contribute knowledge that is used in decision making process. Data handling and presentation in the agricultural decision making process is for the first time in Estonia embedded into field-specific GIS. This approach has significant advantages compared to traditional maps and databases. First, while a small amount of information is easy to obtain from traditional maps it is much more difficult to retain a large bulk of quantitative data, or to interpret spatial relations. Another limitation of paper maps is the problem of updating data and entering the changes. Outputs from DSS are also applicable for development plans of local municipalities and for identifying LFAs requiring additional subsidy schemes. The identification of LFA areas in Estonia took account of weighted average soil quality points for each rural municipality as one of the criteria. The proposed DSS can provide information for more precise spatial differentiation of LFAs.

As the market of agricultural products is unstable, production is related to high economic risks. Accurate, timely, detailed price information is important for good decision making (Hubbard et al. 2000; Adesina and Ouattara 2000; Shively 2001). Therefore the economic models in DSS should be continuously adjusted according to the current market conditions. The selling price, in the study area of unfertilised barley must be by 50% higher to achieve profitability comparable to that gained from the production of fertilised barley (I). When the non-fertilised variant is conditionally equated with organic farming then the evidence indicates that the profitability of organic farming depends initially on the level of additional subsidies, because in the current market situation of Estonia, it is unrealistic to gain such a high price-premium for organic barley.

It is possible in mixed farming to estimate profitability of barley production by converting barley through animal husbandry to pork or milk. Considering the current market situation for grain, pork and milk, the best price is most definitely guaranteed in milk production. Although converting barley at current milk prices would mean that the proportion of unprofitable land in the study area would be less than 10% (I), it should be taken into account that when the cost price of barley exceeds the market price of fodder barley, the profitability of milk production will decrease significantly. If the cost price of self-produced barley exceeds the market price of fodder barley then it is not profitable to grow barley for feed. In this case, it is more profitable for the milk producer to use imported concentrated feed than to produce fodder barley himself.

Development of current DSS is based on available vector maps and databases which allows its implementation across the whole of Estonia. This approach relieved the main drawback of model based DSS in that input values for models are unavailable or expensive to collect (Parker and Campion 1997). Estonian soils have been reasonably well studied (Reintam et al. 2003) and supplementing soil maps with land use maps allows analysis of the production potential and the land-use suitability of each agricultural field. Nevertheless the existing soil data are rarely involved in the decision making process (Kölli 2001) whereas the current DSS makes soil information more self-explanatory and accessible for stakeholders. The shortcoming of available digital soil map is that the most of the data in the database are in a string format and this complicates application of agronomic or environmental models. Further, the soil database should be definitely appended with quantitative parameters, which would provide prerequisites for its more extensive applications. Further to the information drawn from soil databases, the knowledge of the agro-chemical characteristics of each agricultural field is needed, which serves as a basis for optimisation of fertiliser norms. The last nationwide agro-chemical survey of arable soils originates from the late 1980s and not all those maps are yet digitized.

Matthews et al. (2005) showed that the most desired features that stakeholders expect from agricultural DSS are (i) to visualise land use scenarios as computer based maps (69%), (ii) faster decision making due to all the information coming from a single source (60%), (iii) to account for social, economic or environmental criteria (60%), and (iv) quick and easy production of alternative scenarios (59%). The capacity of the current spatial DSS to cover the stakeholders’ expectations of its capabilities creates a solid basis for its further development and application. Despite the fact that this study presents the use of the spatial agro-economic DSS on the example of just one rural municipality and one crop, its importance is more extensive. Assessment and optimisation of land use and of the production potential of agriculture with GIS can serve as a basis not only for drawing up regional development plans but also, and primarily, for advisory service, for advanced education and for development of national agricultural and land use policies. This case study serves as a methodological approach for further development of field-specific resource management in modern agriculture and can be used as a tool in knowledge-based decision making processes throughout Estonia. The importance of this DSS is that information from different sources is...
collected, processed and integrated to unit system. Leck Jensen et al. (2000) noted in the example of Pl@nteInfo developed in Denmark that integration information components increase the value of information for end users. Improvement of DSS should focus on the development of the agronomic models for various crops. This study creates possibilities not only for field-specific agro-economic analysis but contributes the framework for more expanded GIS-based DSS in various branches. The drastic decline in agricultural land use in the transition period (II) has raised the need for land use planning tools of abandoned land. Therefore a developed system can be expanded for decision support for bio-energy production or for afforestation of abandoned and uncompetitive agricultural land. Knowledge-based agriculture presumes effective use of available resources through which production can increase and decrease pressure on the environment. Scientific information in the current DSS, collected during more than last 80 years, is evaluated through various agro-economic models operating in time and space. This is the first time in Estonia that a DSS has been developed with GIS linkages for knowledge-based resource management in agriculture.

6. CONCLUSIONS

According to the main objectives of the study, the following conclusions could be presented:

1. The drastic decrease in arable land use in the transition to a free market economy continued until EU CAP was implemented in Estonia. The regional differences in land use changes in the 1990s were determined mainly by local bio-physical disadvantages such as soil quality. The higher decrease rate of arable land use in 1992–2001 occurred in the regions with low soil fertility. A decrease in soil fertility by one quality point brings about a 2.5% increase in the proportion of abandoned land. The loss of subsidies at the beginning of the transition period highlighted the importance of pedo-climatic conditions in the formation of the profitability of agricultural production but the EU agricultural policy has again relieved the impact of bio-physical diversity on the competitiveness of agriculture.

2. Plant nutrient balances of Estonian arable soils were analysed in the long-term (1939–2003) with uniform methodology. This approach enabled the evaluation of some aspects of sustainability of agricultural land use and soil management through transition from the Soviet era to the open market economy. The application of both mineral and organic fertilisers started to increase in the 1960s and peaked in the 1980s. The increase in fertilisation was not followed proportionately by yield increase and this resulted in positive NPK balances of arable soils in the 1970–1980s, which has significantly improved the nutrient supply of arable soils. The quantities of plant nutrients N, K and P applied to the fields exceeded the amounts removed through crop harvesting by a factor of 2–2.3 (N), 1.9–2.2 (K) and 3–3.5 (P). The amounts of lactate soluble P and K increased by 1.1 and 0.7 mg kg\(^{-1}\) soil per year, respectively.

3. In the 1990s the use of fertilisers has decreased by significant factors: N by six; P by twenty; K by thirty and organic fertilisers by four. The total balances of K and P of arable soils have become negative as a consequence of inadequate fertilisation. Active balance, which enables the estimation of the degree to which formation of the yield occurs at the expense of soil resources, shows that at present the
largest deficiency is regarding P (68%) and K (57%) followed by N (34%). Thus, at present, crop production takes place largely at the expense of the soil nutrient reserves created by farmers in the 1970–1980s. The use of mineral fertilisers is less intensive in the regions with low soil quality. Decrease in soil fertility reduces the amount of mineral fertilisers used by 2.85 kg NPK per one soil quality point. As nutrient deficiency is highest for forage crops, the depletion of soil P and K may become critical, especially in organic systems where grasslands are dominant. Agri-environmental policy should more consider soil degradation due to the negative plant nutrient balances of arable soils in Estonia.

4. At present only 40–50% of the yield potential of cereals is realised in actual farming conditions. The high yield gap indicates the ineffective use of pedo-climatic resources and this causes agricultural self-sufficiency at the national level to deteriorate. Low realisation of yield potential of cereals is partly due to the insufficient use of fertilisers, as the actual yield level is limited by low input of plant nutrients to the soil. It must, therefore, be considered that the yield formation of cereals is largely determined by the pedo-climatic conditions (50–60%), and that fertilisers are a lesser influence. In the case of oilseed rape the utilisation of the yield potential is 60–65%, which is induced by more intensive fertilisation compared to cereals. To narrow the yield gap in a profitable and environmentally friendly way, the field-specific fertiliser and other input optimisation is required.

5. A positive effect of the collapse of Estonian agriculture has been a reduction of the pressure on the environment whereas a negative effect to the several aspects of sustainable agriculture has emerged (i) in soil degradation which is due to insufficient investments into maintaining soil fertility, (ii) in ineffective use of pedo-climatic resources, (iii) in low profitability and competitiveness of the agriculture sector, and (iv) in decreased national food supply. To achieve more sustainable agriculture the optimisation of agricultural land use and soil management should be based on the scientific knowledge and from this necessary precondition to develop a spatial agro-economic DSS.

6. The agronomic models for spring barley and potato, based on the regression analysis of numerous field experiments, were developed to assess the impact of soil and climate conditions on the effectiveness of fertilisers. The effectiveness of fertilisation depends, to a large extent on, besides soil properties, meteorological conditions. The variance of the average effectiveness, even of quite small rates, of mineral fertilisers (N, P, and K) is very high. Higher efficiency is guaranteed in the case of balanced fertilisation but the optimum combination of nutrients depends on the relative prices of fertilisers and yield. The developed models enable the estimation of the pedo-climatic and economic risks in fertilisation optimisation. Improved agronomic models operating in spatial and temporal scale are forming a basis for knowledge-based DSS.

7. Data handling and presentation in the agricultural decision making process was for the first time in Estonia embedded to field-specific GIS and its application possibilities were analysed in the example of Kullamaa rural municipality. A field-specific database was compiled and agro-economic models were applied to provide information for decision makers. Economically effective N norm for barley is, in most of the study area, from 50 to 60 kg N ha⁻¹ but on a quarter of arable land in the study area it is uneconomical to apply N to barley. Field-specific fertiliser optimisation compared to uniform fertiliser application can help farmers to avoid economic losses and simultaneously increase effectiveness of fertilisation and low yields. The simulated barley yield for the study area is, with the use of economically optimised amounts of NPK fertilisers, 2.6 Mg ha⁻¹, which is by 1.1 Mg ha⁻¹ higher compared to the actual cereal yield in the region. Composed thematic maps enable the clear presentation of spatial variability in the profitability of barley production from field to region scale. Farmers can use spatial profitability data with other criteria for crop rotation planning and for strategic decisions but presented DSS does not make decisions, but rather contributes knowledge that can be used in the decision making process. The benefit of this DSS is that information from different sources is collected, processed and integrated into a unified system which makes decision making more effective. This also makes existing soil information more easily available and self-explanatory for stakeholders.

8. Despite the fact that this study presents spatial agro-economic DSS on the example of just one rural municipality and a single crop, its importance is more extensive. Up-scaling the modelling results
from field-level also enables its application in regional planning and in macro-economic analysis. In this study the methodology for the functioning of the DSS was developed which is further applicable nationwide. There is an increasing demand for the planning of abandoned agricultural land in Estonia and a developed DSS can be expanded for the cultivation of bioenergetic crops or for afforestation of abandoned land.

9. Further improvement of DSS should focus on the development of agronomic models for various crops and economic models should be continuously adjusted according the changes in socio-economic conditions. The database of digital soil map should be definitely appended with quantitative parameters, which would provide prerequisites for its more extensive applications such as related production activities to environmental impact.

The extensification of Estonian agriculture during the transition period has reduced the negative impact on the environment but at the same time this has caused a decline in the fertility of agricultural land, and this diminishes the competitiveness of Estonian agriculture. Analysed spatial DSS serves as a basis for effective resource management in modern agriculture and can be used as a tool in knowledge-based decision making processes to achieve economic, social and environmental targets of sustainable agriculture. The improvement of the current DSS and usage expansion from pilot areas to nationwide coverage of Estonia are essential for these purposes. This study creates possibilities not only for field-specific agro-economic analysis but also contributes a framework for further expansion of the capabilities of GIS-based DSS in various branches of the rural economy.

7. REFERENCES


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KOKKUVÕTE


2. Ühtselt metoodikal pühinev haritava maa kasutamine suurendab toimiklastes taimetoiteelementide kasutamisväärtusi, mis võimaldab toimiklasteks asendada mulda viivaid väestepõllumajandusele.

3. Mulda viivad taimetoiteelementide kasutamine võimaldab toimiklastel kasvama kasvamistest tulenevate raskustest ning võimaldab toimiklaste kasvamisvajaduse täitmisel kasvada.

Käesoleva uurimistöö käigus võeti kokku Eesti agraarteaduses senitehtu ning selle põhjal koostatud agromajanduslikud mudelid seostati ühtsesse geoinfoniühendusega. Agromajanduslike mudelite ja asukohapöhised nõuandesüsteemi väljaõttumiseks vajalikud lähteandmed allikaks olid arvukad disertatsioonid, teaduspunktsioonid ja -arvendid, riiklike sordlivõrdluskasutad, agrometteopunktid, loomade jõudluskontrollid, loodus- ja keskkonnakaitse, Statistikaameti, Maa-ameti, Põllumajanduse Registrit ning Informatsooni Ameti, põllumajandusliku kasutamise eesmärgidest teatud FADN, agroekimieenimistusest ja asutustest andmebaasis.

Toös püstitatud eesmärkidest lähtuvalt saab tehakse järgmised järeldused:


2. Ühtselt metoodikal pühinev haritava maa kasutamine suurendab toimiklastes taimetoiteelementide kasutamisväärtusi, mis võimaldab toimiklasteks asendada mulda viivaid väestepõllumajandusele.

3. Mulda viivad taimetoiteelementide kasutamine võimaldab toimiklastel kasvama kasvamistest tulenevate raskustest ning võimaldab toimiklaste kasvamisvajaduse täitmisel kasvada.
ning fosforit viidi mulda 3–3,5 korda rohkem. Märkimisväärsest positiivsest taimetoiteelementide bilansist tulenevalt suurenus sel perioodil muldade lakaatlahustuva fosfori- ja kaaliumisisaldus aastas vastavalt 1,1 ja 0,7 mg kg mulla kohta.

3. Eesti taasiseseisvusjärgsel perioodil, 1990ndatel aastatel, vähenes lämmastikvääte kasutamine kuni 6 korda, fosforvääte kasutamine 2 korda, kaaliumvääte kasutamine 3 korda ja orgaaniline vääte kasutamine 4 korda. Tulenevalt ebapiisavat väetist seonud kasutusest muutus põllumulde lämmastik- ja kaaliumi ekspressse negatiivsena ning lämmastik- ja kaaliumi ekspressse on kasvanud 1,1 ja 0,7 mg kg mulla kohta.

3. Eesti taasiseseisvusjärgsel perioodil, 1990ndatel aastatel, vähenedes lämmastikväetiste kasutamine kuni 6 korda, fosforväetiste kasutamine 20 korda, kaaliumväetiste kasutamine 30 korda ja orgaaniliste väetiste kasutamine 4 korda. Tulenevalt ebapiisavat väetist kasutusest muutus põllumulde lämmastik- ja kaaliumi ekspressse negatiivsena ning lämmastik- ja kaaliumi ekspressse on kasvanud 1,1 ja 0,7 mg kg mulla kohta.

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väetustarbele tagaks uurimiseks arvutuslikuks saagikuseks 2,6 Mg ha\(^{-1}\), mis on 1,1 Mg ha\(^{-1}\) võrra suurem antud piirkonna tegelikust teravalja saagikusest viimisel kümnedil. Koostatud teemakaardil võimaldavad selgelt visualiseerida odrakasvatuse tasuvuse ruumilist varieeruvust nii üksikute põldude tasandil kui ka regionaalselt. Põllumajandustootjaid saavad kasutada põllupõhiseid tasuvusearvutusi koos täiendavate kriteeriumitega näiteks külvikordade planeerimiseks ja strateegiliste välilõikute tegemiseks, kuid antud nõuandesüsteem ei tee otseiseid iseenesest, vaid pakub pigem teaduspõhiist lisainformatsiooni otsustusprotsessi tõhustamiseks. Erinevatelt allikastest päritelisest integreerimine ühtsesse süsteemi suurendab informatiroomi väärtust, kättesaadavust ja teadustulemustest rakendatavat kasutust sõltumaks järk-järgu tasuvikut põllumajanduse eesmärke.


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Decision support system for agricultural land use and fertilisation optimisation: a case study on barley production in Estonia

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The success of the decision support systems, developed within GIS with application of different models, depends on the quality of initial data and the models themselves as well as on the possibilities of their linking. The aim of the present study was to analyse the application of different agro-economic models in a computer-based decision support system, developed for optimisation of agricultural land use and fertilisation, on the example of barley production of Kullamaa rural municipality in Estonia. The algorithms used in the agronomical models were obtained from the regression analysis of numerous field experiments. The calculated new agronomical values serve as a basis for the application of economic models. GIS and modelling remain as two separate systems with the capacity for information exchange between them. Profitability of barley cultivation varied in a very broad range in the study area. The optimal fertiliser amounts established for each field allow increasing crop productivity in the region and at the same time preventing environmental pollution due to production intensification. The proposed decision support system can be further supplemented by several agro-economic models and implemented throughout Estonia.

Key words: barley, fertilisation, geographical information system, land use, decision making, risk factors, soil map

Introduction

The profitability and sustainability of agricultural production depends largely on the comprehensive knowledge of the quality of land as a means of production as well as on the consideration of it in the planning of land use in the whole region. Agriculture more than any other branch of production is influenced by various natural, anthropogenic and economic risk factors on which the profitability of production and preservation of the environment in rural areas depend. Suitable areas for agricultural use are determined by biophysical and socio-eo-
nomic factors. Rational decision making can only be carried out through a multi-criterion evaluation of available input values for optimal decision making are availability of reliable information and the ability to handle it. Natural resources are extremely variable on the spatial and temporal scales. The larger the spatial or temporal scale, the more complex will be the process of exploring and predicting agricultural land use (Stoorvogel and Antle 2001). Geographical information systems (GIS) are widely used for handling spatial information. The application of GIS in land use and fertilisation has been described in numerous papers (Rao et al. 2000, Voivontas et al. 2001, Kalogirou 2002, Sedogo et al. 2002, Roumell et al. 2003, Tianhong et al. 2003, Morari et al. 2004). Geographical information system is a highly useful tool for storing, processing and manipulating spatial databases. In order to expand the application of GIS in agriculture, different (agro-economic) models should be integrated in a GIS system. The success of the decision support systems (DSS), developed within GIS with the use of different models, depends on the quality of initial data and the models themselves as well as on the possibilities of their linking. Decision support systems are computer-based frameworks for integrating data and expert opinions with models, which enable finding different solutions when analysing a particular problem. Such an approach allows flexibility of different activities; like land use planning (Matthews et al. 1999), Ceballos-Silva and Lopez-Blanco (2003) and allocation (Carsjens and Knaap 2002, Wang et al. 2004), fertilisation (Tianhong et al. 2003), biomass production (Vöivontas et al. 2001), environmental protection (Aspinall and Pearson 2000), nutrient balances (Sacco et al. 2003), nature conservation (Geneletti 2004). One of the main reasons for the lack of model based DSS is that input values for models are unavailable or expensive or difficult to collect (Parker and Campion 1997).

In decision making for land use planning and utilisation of resources, a large-scale soil map and supplementary databases form an important component of DSS (Reintam et al. 2003). Supplementing digital soil maps with land use maps allows analysis of the production potential and the land-use suitability of each agricultural field. Besides the information drawn from soil databases, the knowledge of the agrochemical characteristics of each agricultural field is needed, which serves as a basis for optimisation of fertiliser norms.

The aim of the present study was to analyse the application of different agro-economic models in a computer-based decision support system, developed for the optimisation of agricultural land use and fertilisation, on the example of barley production. Barley is the most important field crop in Estonia, accounting for 45–50% of the total area of cereals.

Material and methods

Study area

A GIS including database of soil properties was developed covering the fields (5,000 ha) of the arable land of Kullamaa rural municipality. Kullamaa rural municipality is located in western Estonia. Its total area is 224 km² of which the agricultural area makes up 22%. The average cultivation area of cereals per enterprise is 67 ha. In 1992–2000, the actual average productivity of cereals in the studied area was 1.5 Mg ha⁻¹ and the variation coefficient of the yield was 23%. Inadequate application of fertilisers is among the main causes of the low and unstable yield. In the period 1996–2000, cereals received 39 kg NPK ha⁻¹ in the form of mineral fertilisers and 3.8 Mg ha⁻¹ organic fertilisers. Mineral fertilisers were only used in 46% and organic fertilisers in 6.4% of the total growth area of cereals. To ensure more efficient and stable cereal production, it is essential to optimise fertilisation and to provide location-based recommendations for it.

In the current study, DSS, developed within GIS with the use of different models, developed covering the fields (5,000 ha) of the arable land of Kullamaa rural municipality. Kullamaa rural municipality is located in western Estonia. Its total area is 224 km² of which the agricultural area makes up 22%. The average cultivation area of cereals per enterprise is 67 ha. In 1992–2000, the actual average productivity of cereals in the studied area was 1.5 Mg ha⁻¹ and the variation coefficient of the yield was 23%. Inadequate application of fertilisers is among the main causes of the low and unstable yield. In the period 1996–2000, cereals received 39 kg NPK ha⁻¹ in the form of mineral fertilisers and 3.8 Mg ha⁻¹ organic fertilisers. Mineral fertilisers were only used in 46% and organic fertilisers in 6.4% of the total growth area of cereals. To ensure more efficient and stable cereal production, it is essential to optimise fertilisation and to provide location-based recommendations for it.

The structure of a decision support system and data sources

To develop agro-economic models necessary for the implementation of DSS, a complex database was created using the information of scientific dissertations, publications and reports; the results of variety comparison experiments; the databases of agro-meteorological stations; the data of the Animal Recording Centre; the databases of the institutions of nature and environmental conservation, the Agricultural Registries and Information Board, and the Agrochemical Service of Estonia. Such an up-to-date analysis of the large-scale database, covering the whole agricultural production, allowed us to develop the agro-economic and economic models of the productivity and yield quality of particular field crops as well as of the production and marketing of products of animal husbandry. This approach also allowed, on the basis of the models, to assess the degree of the probability and impact of natural and economic risk factors in case of different methods of land use and agricultural strategies.

A shortcoming of computer-based DSS in agriculture is often unavailability of required input data (Parker and Campion 1997). To overcome this disadvantage in the development of DSS, we processed data from available vector maps and databases. The aim of this approach was the feasibility of optimisation of agricultural land use at different levels, making use of the materials collected by various state agencies and research institutions. Such an approach allows implementation of the developed DSS across the whole of Estonia.

The main component of the system is the map layer of the arable fields (Fig. 1). The initial data for each field used in agronomic models were soil quality points (on a 100-point scale), humus content (determined by Tjurin method), and content of available phosphorus and potassium (determined by Egner-Riehm double lactate method). The calculated new agronomical values serve as a basis for the application of economic models. The new agro-economic values for each field and the compiled thematic maps or tables can be used in decision making processes. Proceeding from the calculated agro-economic characteristics, it is possible to assess the optimal use of each field not only as well as the development potential of the whole region. For this, is possible up-scale the modelling results from field-level to regional level (Saarnikkö 2000, Tan and Shibasaki 2003). Information flow for decision makers and stakeholders is possible from output data of DSS models or directly from input data layers. Non-spatial information flow (including expert opinions) to the DSS is essential to develop agroeconomic and economic models and to supplement the decision making process. In the development of GIS, the software systems MapInfo Professional and MicroStation Geographics were used. There are several approaches to combine GIS with modelling (Sui 1998). In the current DSS, GIS and modelling are in a loose coupling category that integrates GIS with analytical models through the exchange of data files. Neither agroeconomic nor economic models are directly associated with GIS. This approach requires little investment in software development (Matthews et al. 1999). Fedra (1996) proposes an integrated framework in which GIS and modelling remain as two separate systems with the capacity for information exchange between them. The calculations based on the algorithms used in the models were made using MS Excel and the new values were then uploaded to GIS.

The polygons of the fields were mapped by the Estonian Agricultural Registry and Information Board (ARIB). Digitalisation is based on the ortho-photos obtained from the Estonian Land Board. Each agricultural field is supplied with a unique identification number, which allows joining the databases of ARIB in GIS. The databases of ARIB provide additional information for decision making.

Using GIS environment, topology analysis of the field layers and soil map polygons was performed (Fig. 1). The generated database with soil characteristics can provide input values for models used in DSS. For analysing the soils of agricultural land, a digital soil map (scale 1:10,000) was used. The scale 1:10,000 is appropriate for decision making at the field level (Avery 1987). In Estonia,
digital soil maps, covering the whole territory, as well as maps of the lime and fertiliser requirements of arable soils have been compiled. The database supplementing the digital soil map includes the following data: soil type, texture abbreviation, thickness of the epipedon, classes of stoniness, and soil quality points. As most of the data in the soil database are in a string format, the application of these data in models for generating new values is limited. Further, the soil database should be definitely appended with quantitative parameters, which would provide prerequisites for its more extensive application.

Assessment of soil quality points is based on soil crop productivity: there is a linear relationship between quality point and crop yield. Soil quality points are usually determined for each soil-mapping unit and further it is possible to calculate average soil quality for each management unit. To assess the cultivation value of soils, the points of soil suitability indexes for selected field crops were also entered in the database (Fig. 1). The soil suitability index (0–10 points) developed for the conditions of Estonia takes into account the productivity of different soils by the main crops (Valler 1973, Kõlli 1994).

The soil quality points and the data of humus content were drawn from the databases of the Land Board. The data of soil available phosphorus and potassium were obtained from the archives of the Estonian Agricultural Research Centre. As in the 1990s the determination of fertiliser requirement in Estonia practically stopped, the results of the last (in 1985–1989) nationwide determination were employed. This enabled the evaluation of soil nutrient requirement for the entire study area and, proceeding from this, to identify the possibilities of DSS application. In 2002 the state supported determination of fertiliser requirement was restarted and the results of the current determination will be entered directly in the GIS. This serves as a solid basis for the implementation of the developed DSS for the optimisation of fertilisation throughout Estonia. Since one soil sample in both previous and current agro-chemical soil survey represents 3.5 ha, then these data are suitable for modelling and decision making at a field-scale.

### Agronomic and economic models

Integration of the initial data, related to each agricultural field, in agronomic models enables calculation of new agronomic values such as productivity, effectiveness of fertilisers, etc. The algorithms used in the agronomical models were obtained from the regression analysis of numerous different field experiments. The relationships between barley yield and soil properties and fertilisation were established using a database containing the results of more than 600 field experiments conducted in Estonia.

The yield of barley was found for the non-fertilised variant the yield depends on soil humus content, and the effect of nitrogen fertilisation and to estimate weather related variability the following regression equation (r² = 0.84, SE = 0.318, P < 0.000) was applied:

$$ Y_2 = 1.288 - 0.0343 SQ - 0.0383 P + 0.0002811 - 0.0000001635P^2 $$

where $Y_2$ is the yield for non-fertilised barley (Mg ha⁻¹), $SQ$ is soil quality points and $P$ is probability (%). In the current study probability at 50% is used, which represents yield as an average over many years.

In the fertilised variant the yield includes also the increase from the addition of an economically effective norm of NPK. The use of an agronomically effective fertiliser norm ensures a maximum grain yield and the use of an economically effective fertiliser norm ensures the highest profit. The agronomically and economically effective fertiliser norms for barley are calculated from the quadratic yield response curves for different soil nutrient supply levels ($r^2 = 0.93-0.99$; SE = 0.1–0.15; P < 0.05). A general form of the quadratic yield response equation is the following:

$$ Y = a_1 + a_2 x + a_3 x^2 $$

where $Y$ is the yield (Mg ha⁻¹) and $x$ is amount of fertiliser (kg ha⁻¹).

The agronomically effective amount of fertiliser (kg ha⁻¹) is calculated as follows:

$$ X_{a} = \frac{a_1}{2a_2} $$

and the economically effective amount of fertilizer (kg ha⁻¹) is calculated as follows:

$$ X_{c} = \frac{a_1 (P - C_1) - C_2}{2a_2 (P - C_1)} $$

where $P$ is the price of the yield (€ Mg⁻¹), $C_1$ is the cost of fertilisation (€ kg⁻¹) and $C_2$ is the cost of harvesting (€ Mg⁻¹).

To calculate the profitability of barley cultivation ($R$, %), we used the following formula:

$$ R_t = \left( \frac{P \cdot Y - C_1 x + C_2}{C_1 x + C_2} \right) \times 100 $$

where $C_1$ denotes all other production expenses (€ ha⁻¹) such as salaries, depreciation etc.

To estimate the effectiveness of fertilisers, depending on soil humus content, and the effect of climatic conditions, the following regression equation ($r^2 = 0.68$, SE = 5.98, P < 0.000) was solved:

$$ Y_{ag} = \frac{38.649 - 1.744 H - 0.487P + 0.003323 P^2 - 0.0000001677 P^2}{C_1 x + C_2} $$

where $Y_{ag}$ is average effectiveness (kg kg⁻¹) of the nitrogen fertiliser norm $N_{ag}$, $H$ is soil humus content (%) and $P$ is probability (%).

To calculate economically effective rates, the cost of fertilisation and the harvesting costs of yield increase, as well as the returns from yield increase, are considered. Depending on soil humus content and the available content of $P$ and $K$, the...
Results and discussion

Soil resources

The soils of the study area are dominated by different gleysols (43.5%) among which the proportion of Mollic Gleysols is the largest (Table 1). The share of automorphic and gleyic Calcaric Cambisols is also appreciable. Regarding soil texture, the most common texture is sandy loam (56.1%). Heavy texture occurs mainly in Mollic Gleysols. Peat soils account for 8.3% of arable land in the area. Because of the large proportion of hydromorphic soils, the state of drainage has become an important criterion for soil fertility and soil suitability. The area not requiring drainage makes up 21.6%. A total of 62% of arable land is drained. As in the 1990s investments in land amelioration were minimal, it can be supposed that the condition of the former drainage systems has considerably deteriorated.

The average quality of all arable land in Estonia is 39 points. Average field soil quality in study area is 37 points. In different fields, soil quality ranges between 22–52 points. The area with very low soil quality (<30 points) makes up 9.5% (Table 2). The share of soils with low humus content in the study area is small. The fields with soil humus content less than 3% only account for 8.6%, while humus-poor soils (humus content less than 2%) are absent. The fields with low soil available phosphorus and potassium account for 17.1 and 13.9%, respectively. Of all arable land, less than one-fourth is characterised by soils with high phosphorus and potassium content.

To assess soil suitability for the study area, the database was supplemented with soil suitability indexes (scale 0–10 points) according to different criteria (scale 0–10 points) according to different crop types. The more suitable is this soil for cultivating a particular crop, the total area of the soils with a high cultivation value (9–10 points) for barley accounts for 28.7% (Table 3). At the same time, it should be taken into account that the area of the soils with a low cultivation value for barley production is large. However, the soils of the study area are relatively favourable for cultivation of field grasses, for which lands with a cultivation value higher than 6 points constitute 95.9%.

Effective norms of mineral fertilisers

Agronomically effective fertiliser norms for barley, ensuring a maximum yield, depend on soil fertiliser requirement and vary in very large limits in the region: maximum up to 103 kg ha⁻¹ for nitrogen, and 27 kg ha⁻¹ and 60 kg ha⁻¹ for phosphorus and potassium, respectively. Effective fertiliser rates decline with increasing soil NPK supply. Soil N supply is evaluated according to soil humus content. As there is strong correlation between total soil nitrogen content and soil humus content (r² = 0.97; SE = 0.019; P < 0.000), it is possible to estimate the need for nitrogen fertiliser proceeding from soil humus content (Roostalu et al. 2003). For each arable field, agronomically and economically effective norms of nitrogen fertiliser were calculated on the basis of soil humus content (Fig. 2). To generate such an equation, previously effective fertiliser norms were determined for several soil nutrient supply levels. Although use of agronomically effective fertiliser norms ensures a maximum yield, this practice is not economically justifiable.

Table 1. Soil composition of arable land in Kullamaa rural municipality.

<table>
<thead>
<tr>
<th>Soil group by WKB*</th>
<th>Soil texture, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>Fluvisols</td>
<td>1.3</td>
</tr>
<tr>
<td>Calcaric Cambisols</td>
<td>16.9</td>
</tr>
<tr>
<td>Gleysic-Cambisols</td>
<td>19.1</td>
</tr>
<tr>
<td>Rendic Leptosols</td>
<td>1.0</td>
</tr>
<tr>
<td>Mollic Gleysols</td>
<td>35.7</td>
</tr>
<tr>
<td>Calci-Cambisols, Dystric, etc. Gleysols</td>
<td>7.8</td>
</tr>
<tr>
<td>Mollic Cambisols, Cutanic Luvisols</td>
<td>2.4</td>
</tr>
<tr>
<td>Gleysic Cambisols and Luvisols</td>
<td>7.4</td>
</tr>
<tr>
<td>Alterisols</td>
<td>0.2</td>
</tr>
<tr>
<td>Histosols</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Table 2. Soil quality and humus content of arable land in the study area.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Intervals</th>
<th>Distribution, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil quality points</td>
<td>&lt;30</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>31–35</td>
<td>33.6</td>
</tr>
<tr>
<td></td>
<td>36–40</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>41–45</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td>46–52</td>
<td>10.9</td>
</tr>
<tr>
<td>Soil humus content</td>
<td>2.0–3.0</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>3.1–4.0</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>4.1–5.0</td>
<td>34.3</td>
</tr>
<tr>
<td></td>
<td>5.1–8.0</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>&gt;12.0</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Table 3. Soil suitability index for barley and field grasses for arable land in the study area.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Soil suitability index, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Spring barley</td>
<td>12.9</td>
</tr>
<tr>
<td>Field grasses</td>
<td>4.1</td>
</tr>
</tbody>
</table>

* The names of the soil groups are given according to the system of World Reference Base for Soil Resources.
fied, as at a certain point the profit gained from an additional amount of fertiliser is lower than the extra costs. On soils whose humus content is higher than 10%, it is unprofitable to apply nitrogen fertilisers for barley. Field experiments conducted with barley in Canada have shown that the net value of returns from P fertilisation increased with increasing P rate up to approximately 23 kg P ha⁻¹ (Nyborg et al. 1999).

Compared with the agronomically effective fertiliser norms, the economically effective fertiliser norms, which guarantee a maximum profit in barley production, are 23% lower for N, 12% lower for K, and as much as 59% lower for P (owing to the high prices of P fertiliser). Economically effective N norms range from 50 to 60 kg ha⁻¹ on 67.1% of agricultural land (Fig. 3). As the soils of the study area are largely humus-rich, the effectiveness of nitrogen fertilisers and their optimal amounts remain relatively low. However, at the same time, it is not economically reasonable to use nitrogen fertilisers for barley on 18.7% of the land.

Field-specific fertiliser recommendations will increase the profit and the nutrient use efficiency as well as will reduce negative impacts on the environment (Sacco et al. 2003, Brown et al. 2005). An excess of N and P can lead to eutrophication and to groundwater pollution (Oborn et al. 2003). The fertiliser norms found on the basis of soil fertiliser requirements for barley production in a particular region are also consistent with environmental and legislative restrictions. The developed DSS improves the level of crop productivity in the region and at the same time prevents pollution of the environment due to fertilisation. Proceeding from the soil database, it is possible to establish an agro-economically and environmentally grounded fertiliser norm for each field. Application of such an approach would be especially useful in areas with Nitrate Vulnerable Zones, which are located in regions with intensive agriculture in Estonia.

The effectiveness of fertilisation depends to a large extent on, besides soil properties, meteorological conditions. On the basis of all field trials conducted to date, it can be calculated that in case of application of the N₉₀ fertiliser norm for intensive barley varieties on moderately moist soils, with soil humus content ranging between 2 and 4%, yield increase is 15–18 kg N ha⁻¹. In highly favourable years as much as 25–30 kg of grain can be obtained, with a probability of 10–20%, at the expense of 1 kg of nitrogen (Fig. 4). However, on gleyic and gley soils, richer in humus, this amount of nitrogen can lead to the lodging of the crop and to yield decrease 1–2 years out of ten (Roostalu et al. 2003).

To assess the weather related risk of fertilisation in barley production, the probability of the profit gained from fertilisation was calculated for the N₉₀ fertiliser norm. This fertiliser norm is well consistent with the economically effective amount found for the region. To ensure profit from fertilisation, the average efficiency of N₉₀ must be higher than 5 kg N kg⁻¹. The probability of gaining an economic profit with the application of the N₉₀ fertiliser norm was 79.6% of the studied area higher 80%, i.e. in eight years out of ten. In the remaining area, however, the agro-economic risk with the use of this particular N fertiliser norm was very high due to pedo-climatic conditions. As in some fields the probability of profitable fertilisation is minimal even at low N rates, it is crucial to provide field-specific fertilisation recommendations.

### Profitability of barley cultivation

The yield of barley, the effectiveness of fertilisers and the profitability of barley production depend on soil fertility, weather conditions during growth, soil fertiliser requirement, amount of the fertilisers used and their cost and on the price of the crop. It depends as well on the possibilities of converting the yield into the output of animal production and its price and also on other production expenses and factors. With non-application of fertilisers, the barley yield obtained at the expense of soil fertility remains in the range of 0.7 to 1.8 Mg ha⁻¹. Depending on climatic conditions, the barley yield without fertilisation varies more when soil is less fertile. On poor soils, estimated at approximately 10% quality points, the average barley yield is only 1.0 Mg ha⁻¹, while in unfavourable years the crop may practically fail altogether. With the use of economically effective amounts of NPK fertilisers, the barley yield in the study area ranges from 1.0 to 4.3 Mg ha⁻¹. The average yield in case of the fertilised variant is 2.6 Mg ha⁻¹. The actual farm yield of cereals in the study region is 42% lower. Thus the proposed DSS provides prerequisites for optimisation of barley fertilisation and for increasing the effectiveness of cereals production in general. The average yield of spring cereals, obtained in variety comparison tests, is about 4.5 Mg ha⁻¹. At present approximately only 35–50% of the potential yield of cereals is obtained in Estonia (Roostalu et al. 2001).

Depending on soil properties, the profitability of barley cultivation varied in a very broad range in the study area (Fig. 5). In the current market situation barley production is not economically profitable on 28.3% of agricultural land. On the other hand, the profitability of barley production on 35.3% of agricultural land is higher than 20%. Visualisation of the results by means of thematic maps enables to clearly present spatial variability in the profitability of barley production at the level of the region, farm or field. The maps can be used in field-specific decision making and in allocation of barley production. Farmers can use field-specific profitability data with other criteria for crop rotation planning and for strategic decisions but presented DSS do not make decisions, rather it contribute knowledge that is used in decision making process. Outputs from DSS are also applicable for development plans of local municipalities and for identifying less favoured areas (LFA) requiring additional subsidy schemes. The identification of LFA areas in Estonia took account of weighted average soil quality point for each rural municipality as one of the criteria. The proposed DSS can provide information for more precise spatial differentiation of LFA areas. As the market of agricultural products is unstable, production is related to high economic risks.
The instability of the prices for agricultural products is the main factor, which influences the income of producers and the sustainability of the agricultural sector. According to the data from the Estonian Institute of Economic Research, the farm-gate price of barley was extremely unstable in the period 1999–2004. The variation coefficient of the farm-gate prices of fodder barley, the cereal with the highest production capacity, was 18%. The price of fodder barley was lower than 90 € Mg⁻¹ for 49% of the months in the period 1999–2004 and exceeded 120 € Mg⁻¹ for only a short time (4%). Although the price of food barley was somewhat higher, it has no significant effect on the economic results of the whole sector of cereal production because of the small market size. As an average for the period 1999–2003, fodder barley accounted for 79% and food barley accounted for only 8% of the total consumption.

In case barley is sold at low prices (90 € Mg⁻¹) the proportion of profitable land would be 28%. With a 10 € increase in the price, already 59% of arable land would yield profit (Fig. 6). However, even at high selling prices of barley, the cultivation of this cereal would be unprofitable in some fields. In the production of barley without mineral fertilisers, its selling price must be considerably higher in order to gain a profit equal to that gained with application of economically effective fertiliser norms. In the production of non-fertilised barley, its selling price must be more than 1.5 times higher in order to achieve profitability comparable to that gained from the production of fertilised barley. In the current market situation of Estonia, it is unrealistic to gain such a high price-premium for organic barley. Thus it is evident that the profitability of organic farming depends first of all on the level of additional subsidies. Besides direct sale, it is possible to convert barley into animal products, assessing the economic suitability of agricultural land on the basis of distribution of the profit gained from, e.g. pork or milk production. To gain profit from at least 70% of arable land, the selling price of barley must be higher than 106 € Mg⁻¹. In order to gain the same profit from pork production, the price of pork must be higher than 130 € 100 kg⁻¹ and in milk production the price of milk must be higher than 181 € Mg⁻¹ (Fig. 6). Considering the current market situation, the required price is most definitely guaranteed in milk production. Although in case of converting barley to current market prices the share of unprofitable land would be less than 10%, it should be taken into account that when the cost price of barley exceeds the market price of fodder barley, the profitability of milk production will decrease significantly. If the cost price of self-produced barley exceeds the market price of fodder barley then it is not profitable to grow barley for feed. In this case, it is more profitable for the milk producer to use imported concentrates feed than to produce fodder barley himself.

Conclusions

Agro-economic analysis of land use for different field crops and use of digital maps allow assessing and comparing the effectiveness of the means of production as well as its profitability. Hence estimation of soil fertility and production optimisation of an enterprise or a region should include a complex agro-pedological and economic analysis of land use, of the possibilities of specialisation of production and application of different technologies as well as of the environmental aspects. Assessment and optimisation of land use and of the production potential of agriculture with GIS can serve as a basis not only for drawing up regional development plans but also, and primarily, for advisory service, for advanced education and for development of national agricultural and land use policies. The present study provides some examples of the possibilities of agricultural land use and fertilisation optimisation in one region. The optimal fertiliser amounts established for each field allow increasing crop yields and at the same time preventing environmental pollution due to production intensification. The proposed extensible DSS should be further supplemented with different agro-economic and ecological models and can be used as one tool in knowledge-based decision making processes throughout Estonia.

Acknowledgements. The study was supported by the Estonian Science Foundation grant No. 4819. We would like to thank Estonian Land Board, Estonian Agricultural Research Centre, Estonian Agricultural Registers and Information Board and Ltd. E.O.Map for their collaboration during this research.

References


Fig. 5. Profitability of barley cultivation in the fields of arable land in Kullamaa rural municipality. The number in brackets for each denoted range shows the proportion (%) of this range in the area.

Fig. 6. The proportion of profitable land (%) in different conditions of barley production and marketing depending on the selling price of production. Barley with economically effective mineral NPK and barley—without fertilisation.

Agro-economic analysis of land use for different field crops and use of digital maps allow assessing and comparing the effectiveness of the means of production as well as its profitability. Hence estimation of soil fertility and production optimisation of an enterprise or a region should include a complex agro-pedological and economic analysis of land use, of the possibilities of specialisation of production and application of different technologies as well as of the environmental aspects. Assessment and optimisation of land use and of the production potential of agriculture with GIS can serve as a basis not only for drawing up regional development plans but also, and primarily, for advisory service, for advanced education and for development of national agricultural and land use policies. The present study provides some examples of the possibilities of agricultural land use and fertilisation optimisation in one region. The optimal fertiliser amounts established for each field allow increasing crop yields and at the same time preventing environmental pollution due to production intensification. The proposed extensible DSS should be further supplemented with different agro-economic and ecological models and can be used as one tool in knowledge-based decision making processes throughout Estonia.

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References


Agricultural and Food Science

Astover, A. et al. Decision support system for agricultural land use


Changes in agricultural land use and in plant nutrient balances of arable soils in Estonia

(Veränderungen der landwirtschaftlichen Nutzung und der Nährstoffbilanzen landwirtschaftlich genutzter Böden in Estland)

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Abstract
The aim of the present study was to assess the impact of changes in agricultural land use and in the plant nutrient balances on the degradation of soils in Estonia. The plant nutrient balances of arable soils in Estonia were calculated at the national level. After the re-establishment of the independence of Estonia, in the transition to market economy, agricultural production has undergone a drastic decline. Agricultural land use has declined most of all in the regions with low soil fertility. Decreased and low-input agricultural production has reduced pressure on the surrounding environment but owing to the inadequate use of fertilizers, the balance of the main plant nutrients is at present negative. In the 1990s, crop production has occurred largely at the expense of soil resources. Current agri-environmental policy should be supplemented with measures for preventing degradation of soils due to the depletion of plant nutrient reserves of arable soils.

Keywords: Land use changes, soil nutrient balances, soil fertility, degradation

Introduction
In recent years profound changes have taken place in European agrarian policies, which have significantly influenced the development of rural areas and agricultural production (Bouma et al. 1998). Large-scale reforms occurred in Central and Eastern European countries (Alanen 1999; Trzeciak-Duval 1999; Sarris et al. 1999; Swinnen 1999; Csaki 2000; Burger...
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2001; Turnock 2001). Nowadays, increasingly more attention is given to the sustainable and effective use of natural resources (Park & Seaton 1996; Bade & Kruseman 1998). Besides conventional agriculture, alternative agricultural systems, which can ensure an ecologically cleaner and healthier environment, have gained significantly more importance (Kirchmann & Thorvaldsen 2000; Staniszewska & Schnug 2002). The applied agricultural system determines the efficiency of use of resources (Strulik & Bondarelli 1997; Blun et al. 2002), the nutrient balances of soils (Schröder et al. 1996; Kücke & Kleeberg 1997; Kätterer & Andren 1999) as well as the general state of the environment and agroecosystems (Walden et al. 1998; Roostalu et al. 2000; Kutra & Aksomaitiene 2003). Through increasing the effectiveness of application of plant nutrients in the whole element cycling of the agroecosystem it is possible to reduce pressure to the environment. Proceeding from pedoclimatic conditions, it is necessary to find an optimal level of the intensity of plant and animal production and their proportions on the level of the farm, the region and the state (Granstedt 2000).

After the re-establishment of the independence of Estonia, in the transition to market economy, agricultural production has undergone a drastic decline; the area of arable land has decreased to 53%, cereal production to 53%, meat production to 29% and milk production to 50% of previous level. Gross agricultural output has decreased more than twice during one decade. The collapse of Estonian agriculture has definitely reduced the negative impact of fertilization and use of pesticides on the environment. However, at the same time, there has emerged the issue of degradation of soils, which is due to insufficient investments into maintaining or improvement of soil fertility. Degradation of soils in Estonia is related to erosion, compaction, acidification, insufficient fertilization and other phenomena that degrade soil fertility. Usually, degradation of soils occurs in poor socio-economic conditions. According to the data of FAO (2000), one-third of arable land in Estonia is affected by degradation to a greater or lesser degree. Of all degraded soils in the world about 11% are situated in Europe (Oldeman et al. 1990). The average national and regional soil nutrient balances, based on statistics and on other official information, can be a useful complement to environmental monitoring (Oiboom et al. 2003). The aim of the present study was to assess the impact of changes in agricultural land use and in the plant nutrient balances on the degradation of arable soils in Estonia.

Material and methods

Changes in agricultural land use were estimated on the basis of national statistics and the databases of the Estonian Land Board. Land use changes were associated with soil quality of arable land in order to establish regional influences. Assessment of soil quality on a 100-point scale is based on soil crop productivity: There is a linear relationship between quality point and crop yield. Soil quality points are determined for each soil-mapping unit; further it is possible to calculate average soil quality for each management unit or a region. The nitrogen (N), phosphorus (P) and potassium (K) balances of arable soils in Estonia were calculated at the national level. Estimation of the nutrient balances was based on the data of national statistics for 60-year fertilization, crop structure in land use and crop yields. Total balances were calculated as the difference between the input with inorganic fertilizers, seeds, manure, precipitation (for N), microbiological fixation (for N) and removal of nutrients with harvested products. Active balances were calculated on the basis of the inputs of plant available nutrients. By determination of the utilization rates of nutrients, originating from different sources, by crops, and for estimation of the impact of the nutrient balance on soil fertility, the results of agronomic field experiments conducted in Estonia during 80 years were summarized. Changes in nutrient supplies of arable soils were estimated on the basis of the databases of the Estonian Agricultural Research Centre. The data were processed using correlation and regression analyses.

Results and discussion

Changes in agricultural land use

After the regaining of independence in Estonia, agricultural production, which had been highly subsidised in the Soviet period, became practically unsubsidised, while prices began to form freely. Estonia opened its markets and applied a liberalized trade policy. The exceedingly extensive decrease in plant production has been due to a sharp rise in the prices for machinery, fuel, fertilizers and pesticides, as well as to the unstable and low marketing prices for agricultural products. The cultivation area of field crops has diminished about 39.5 thousand hectares a year. Compared with 1990, the sown area of cereals and legumes has decreased by about 130 thousand ha, the growing area of potato has decreased 2.6 times, or by 28 thousand ha, and the growing area of forage crops has decreased by 485 thousand ha. Only the growing area of industrial crops has increased by 41,000 ha (Figure 1). Owing to the decline in agricultural land use and altered agronomic practices in the 1990s, soil erosion and compaction (Reintam et al. 2001) as well as leaching of nutrients into ground water and surface water (Mander et al. 2000; Iital et al. 2005) have decreased.

Agricultural land use has declined most of all in the rural municipalities located in the regions with low fertility soils (r=0.63, p<0.000) (Figure 2). A decrease in soil fertility by one quality point brings about a 2.5% decrease in the share of abandoned land. Although the population of rural municipalities has also decreased 7.8%, the area of agricultural land on

Figure 1. Area of field crops in Estonia, 1919–2003.
low fertility soils in northern, eastern and south-eastern Estonia as well as around Lake Peipsi and in Hiiumaa Island has decreased 2–10 times per capita. To prevent further abandonment of agricultural land in Estonia, support for less favourable areas was implemented in 2004.

Changes in plant nutrient balances of arable soils

In the period before the restoration of the independence of Estonia, when the state subsidies for agriculture were appreciable, the average amounts of plant nutrients introduced in the soil increased 4.5 kg N, 2.8 kg K and 0.6 kg P ha$^{-1}$ per year. At the same time, the amounts of nutrients taken up by plants and removed with the yield increased on average 1.3 kg N, 1.0 kg K and 0.2 kg P ha$^{-1}$ per year. The amounts of plant nutrients applied to the fields exceeded the amounts taken up by plants 2–2.3 times regarding N, 1.9–2.2 times regarding K and 3–3.5 times regarding P. Due to the positive balance of plant nutrients (Figure 3), the amounts of lactate soluble P and K increased 1.1 and 0.7 mg kg$^{-1}$ soil per year, respectively.

The extremely positive balance of N and P in the 1970s–1980s caused pollution of water ecosystems (Nõges et al. 2005). The excess of plant nutrients can be explained by the low efficiency of fertilizers in the collective farms and state farms of that time (Roostalu et al. 2001).

In the 1990s, plant production has occurred largely at the expense of soil resources as the amounts of N, P and K removed with the yield were 25, 5 and 28 kg ha$^{-1}$ larger, respectively, than the amounts of these plant nutrients introduced in the soil. In 2001, the cultivation area of field crops was 662.8 thousand hectares where on average 43.0 kg N, 5.5 kg P and 20.2 kg K ha$^{-1}$ were introduced in the soil with mineral and organic fertilizers. Taking into account that the agro-economically sound fertilizer norm should be 70–100 kg N, 20–25 P and 50–60 K ha$^{-1}$, it is evident that the fertilizer amounts applied today in agricultural enterprises are drastically insufficient. The average amount of manure used was only 2.4 Mg ha$^{-1}$, while regarding the total amount of nutrients introduced in the soil, 31% of N, 51% of P and 62% of K were covered from manure. A negative plant nutrient balance has deteriorated the status of plant available K and P of arable soils in several post-Soviet countries (Cermak & Budnakova 2005; Katikins & Lipenite 2005; Nikolova 2005).

Application of mineral fertilizers in the current economic situation is only within the power of richer producers and farms situated in areas with more favourable pedoclimatic conditions.

Figure 2. Decrease in the area of arable land (%) in 1992–2001 depending on soil quality points.

Figure 3. Total balances of nitrogen, phosphorus and potassium of arable soils in Estonia, 1959–2003.
There is a strong correlation between application of mineral fertilizers and soil quality ($r = -0.81; p < 0.000$). Decrease in soil fertility reduces the amount of mineral fertilizers used by 2.85 kg NPK per one soil quality point. Due to limited economic resources, the expenses for fertilizers in many enterprises are below 20 € ha$^{-1}$, although 1 € invested in fertilizers will increase total plant production by 5.44 €.

In case of the nutrient balances, it is necessary to take into account that plants utilize only a certain amount of total input. Of the N contained in mineral fertilizers, plants utilize 40–50% in the first year and 50–60% in the whole crop rotation in the pedoclimatic conditions of Estonia. From manure, plants utilize 20–30% and 40–60% of N, respectively. Regarding P, plants use only 10–30% from superphosphate and 20–40% from manure in the first year, 25–45% and 40–60% in the whole crop rotation, respectively. A large part of P introduced in the soil with fertilizers is absorbed chemically. Chemical absorption of the P contained in fertilizers is higher in soils with a heavy texture as well as in the case of large fertilizer amounts and lower content of lactate soluble phosphorus. Utilization of K from mineral fertilizers ranges between 50–70% in the first year and between 60–80% in the whole crop rotation. From manure, plants utilize 50–70% and 70–80% of K, respectively.

Proceeding from the amounts of fertilizers introduced in the soil and from all other balance input, as well as from the coefficients of utilization of nutrients by plants, one can compile an active plant nutrient balance for arable soils (Figure 4). Such a balance allows one to estimate the degree to which formation of the yield occurs at the expense of soil resources. It can be concluded that at present deficit is largest regarding P (68%) and K (57%) followed by N (34%). The difference between the amounts of plant available inputs and the amounts removed with the yield is negative: –24.5 kg N, –6.5 kg P, and –28.2 kg K ha$^{-1}$.

Regarding the N introduced in the soil, it should also be taken into account that various losses account for 30–35% and that 15–20% goes for humus formation. Depending on the plant species, 0.6–1 kg of N from soil resources is utilized per one soil quality point. Of lactate soluble soil P and K, plants uses 9–13% and 20–23% as an average of the crop rotation, respectively.

Based on the results of all fertilization experiments conducted in Estonia until now, it can be concluded that on highly phosphorus-poor soils the content of available P decreases in case of non-use of fertilizers already during the first crop rotation cycle. In order to avoid such a decline, an average fertilizer amount should be no less than 10–15 kg P ha$^{-1}$. In Estonia, however, altogether only 6.8 kg P as an average for 2001–2003 were given with mineral and organic fertilizers per hectare of the growing area of field crops, while the amount left over for forage crops was as little as 1.8 kg P ha$^{-1}$. The limit norm of potassium should be 40–60 kg K ha$^{-1}$. In case of smaller amounts soil will become impoverished in regard to lactate soluble K. As an average for 2001–2003 the total amount of K introduced in the soil with fertilizers was 29.6 kg ha$^{-1}$. According to the agrochemical survey, the share of arable soils characterized by K deficit (low and very low supply level) increased from 43% in 1984–1989 to 47% in 2000–2005. At present, it is difficult to determine actual changes in soil nutrient reserves at the national level because of the incomparable surveys for 1984–1989 (1.1 million ha) and 2000–2005 (170 439 ha). Comparison of changes in soil nutrient supply levels is also complicated (i) due to the sharp decrease in arable land, especially in areas with low soil fertility, and (ii) due to the regional allocation of soil sampling in 2000–2005 to the areas where fertilization was more intensive in the 1990s. To obtain reliable data of changes in soil fertility, resulting from the negative plant nutrient balances in the last decade, the national agrochemical survey of arable soils should be completed. The objective of current EU agri-environmental policy is to achieve less intensive production (Zalidis et al. 2004). For this purpose, the balances of N and P at the field (Tunney et al. 2003) or at the farm level (Brouwer 1998) are employed in Europe. However, applied of agri-environmental measures are inefficient to prevent threat to soil fertility arising from the consistently negative nutrient balances in Estonia.

In the current economic situation agricultural producers can ensure maintaining of soil fertility only in potato cultivation where they are able to give the required amounts of organic and mineral fertilizer. Regarding N, P and K, an active balance has been maintained (Figure 5). In case of cereals, the amounts of plant nutrients introduced in the soil with fertilizers are markedly smaller than the amounts removed with the yield. With regard to N and K, the deficit is 45% and 47%, respectively, while the deficit is particularly high for P, 69%. The most negative nutrient balance is for forage crops.

Consequently, owing to the inadequate use of fertilizers and pesticides, the balance of the main plant nutrients and humus is negative and the weediness of soils has increased to a great extent (Lauristone & Taligre 2003). Highly limited investment in land improvement has deteriorated the drainage condition of hydromorphic soils and has led to an increase in soil acidification.
Conclusion

The transition to a society with market economy in the 1990s as well as the altered socio-economic conditions have brought a decline in the fertility value of agricultural land, which significantly diminishes the sustainability and competitiveness of Estonian agriculture. Decreased and low-input agricultural production has reduced pressure on the surrounding environment. The negative plant nutrient balance of arable soils at the national level in Estonia indicates the need to consider the nutrient balances also on the field scale. Current agri-environmental policy should be supplemented with measures for preventing degradation of soils due to the depletion of plant nutrient reserves of arable soils.

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References

An agro-economic analysis of grain production in Estonia after its transition to market economy

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Abstract. For analysing agronomic efficiency and economic criteria, the results of variety comparison tests of cereals, performed in Estonia during twenty years, national statistics and the data of the survey of the Farm Accountancy Data Network (FADN) for 2000–2003 were summarised. Farms whose grain production contributed more than 75% to total output were selected for analysis. At present only ~40–50% of the real yield potential of cereals is realised. In case of oilseed rape the utilisation of the yield potential is 60–65%. Among the cereals, the largest share is accounted for by barley with 25–43% and wheat with 15–29%. During four years (2000–2003), total inputs increased 21%. Total inputs were the highest in large farms. As an average for 2000–2003 FADN grain producers were profitable in all size groups but consideration of total labour costs indicates that small grain farms were unprofitable. Average farm family income was 1,376 EEK ha⁻¹. There is a non-linear relationship between farm size and economic indicators. Farm family income increases up to ~400 ha. The increase is most significant in the size range 40–200 ha where the increase in farm size by one hectare increases profit by 7.6 EEK ha⁻¹. Further increase will decelerate profit and the most efficient use of labour occurs in this size range as well. Cost benefit is the highest for farm size ranging from ~150 to 400 ha. Profit decreases with the increase in one annual work unit by 508 EEK ha⁻¹ and production becomes unprofitable in case a grain farm employs more than 2.6 workers per 100 ha.

Key words: grain farms, profitability, yield potential, fertilisers, FADN

INTRODUCTION

The total production of Estonian agriculture has decreased more than two times in the period following the regaining of independence. The proportions of agriculture, hunting industry and forestry in the gross domestic product have decreased 2.5 times. The growth area of field crops has decreased 350 thousand hectares, among which the area of fodder crops has decreased 200 thousand hectares, the area of cereal crops 123 thousand hectares and the area of potato 23 thousand hectares. The area of arable land per animal unit is 2.6 hectares and the average yield of fodder crops per hectare of arable area is 23.6 GJ. The total yield of cereals has decreased on average 22.5 Mg per year, which accounts for 3% of initial production. The most drastic decline has occurred in the cultivation of rye and barley, 9.1 Mg or 7% and 23.3 Mg or 4.9% per year, respectively. The growth area has increased for wheat, rape and legumes. In 2000–2003 the total production of cereals was 571.4 Mg; domestic use was 740.5 Mg.
from which import accounted for 26%. The role of import was particularly significant in case of wheat. Considering the yield and its stability, Estonia ranks among the last countries in Europe.

The drastic decrease in crop production is caused by the soaring prices of machinery, fuel, fertilisers and plant pesticides as well as by the unstable and low market prices of agricultural products. Also the national ultra-liberal agricultural policy and a rigid foreign exchange rate may have intensified the decline (Yao, 2005). Agricultural production has become more environment friendly but proportionately less effective. Agricultural production must be both agronomically and economically efficient and environment friendly. The agronomical efficiency of grain production is important in view of both local and global food demand. Considering available biophysical resources, Estonia is capable of at least recovering the average level of self-sufficiency for cereals. Dobermann and Cassmann (2002) have estimated that farm yields must account for 70–80% of the yield potential to cover increasing world food demand. During the last decade, Estonia has been not able to ensure agricultural self-sufficiency.

The competitive ability and profitability of Estonian agriculture have been explored at the state level (Alanen, 1999; Roostalu, 2000; Yao, 2005; Swinnen et al., 2005) and at the regional level (Maidre & Lilover, 2003). Although studies have been made of profitability calculations for grain production (Möller et al., 1998; Vassiliev & Ellermie 2002; Loko et al., 2005), analysis of the real situation in farms specialising in grain production has been lacking. The aim of the present study was to assess the production potential of Estonian grain production and to analyse agro-economic indicators in test farms in 2000–2003. Estimation of agronomic efficiency of grain production was based on the realisation of yield potential in actual production. The analysis of agronomic efficiency and economic indicators allows assessing the sustainability of grain producers.

**MATERIALS AND METHODS**

For analysing agronomic efficiency and economic criteria, the results of variety comparison tests of cereals, performed in Estonia during twenty years, national statistics and the data of the survey of the Farm Accountancy Data Network (FADN) for 2000–2003 were summarised. FADN has been used-under-utilised but it is more capable than presumed (Vrolijk et al., 2004). The yield potential of cereals and oilseed rape was provisionally equalled with the yield obtained in variety comparison tests. The data of the agricultural subsidies for grain production were obtained from the Agricultural Registers and Information Board.

The methodology of FADN enables to extrapolate the data of economic results for the agricultural holdings included in the sample to the agricultural sector as a whole. The Jäneda Training and Advisory Centre is responsible for a FADN survey in Estonia. The current paper uses the FADN terminology.

According to the FADN database, the farms whose grain production (cereals, legumes and oilseed crops) contributed more than 75% to total output were selected. The whole analysed sample consisted of 287 observations. This approach enabled to analyse the agro-economic parameters of specialised grain producing farms, for which correlation analyses were applied. The average size of the farms in the sample was 262 ha. As this figure is markedly higher than the national average, the assessment of economic indicators had to proceed from the difference in the size groups. The grouping of the farms is based on the size of the utilised agricultural area. In some studies (Judez et al., 2001; Judez & Chaya, 1999; Rezitis et al., 2002), the grouping of the FADN farms is based on the European Size Units (ESU). Economic size of the farm in ESUs is obtained by dividing the total standard gross margin of the holding by EUR 1,200. As a farm size in hectares and farm size in ESUs were significantly linearly correlated ($r = 0.95; P < 0.01$), it was possible to carry out grouping on the basis of area.

**RESULTS AND DISCUSSION**

**Yield potential and its utilisation**

The many-year average yields of winter cereals in the case of a near optimum agricultural background are 3.5 Mg ha$^{-1}$ (Fig. 1). In unfavourable years, with a probability of one year out of ten, the yield of rye and winter wheat can be less than 2 Mg ha$^{-1}$. However, in favourable years, with a similar probability, the yield of winter cereals can be 5.5 Mg ha$^{-1}$. In case of extremely severe frost damage, the yield of winter cereals can be even lower than 1 Mg ha$^{-1}$.

Among the studied varieties, the real yield potential of winter wheat in the pedoclimatic conditions of Estonia and with the agro-technology used to date is 7.0 Mg ha$^{-1}$ and the maximum yield of rye in favourable years has been as much as 8.0 Mg ha$^{-1}$. According to the results of variety comparison tests, the yield of spring cereals has been somewhat higher compared with winter cereals. The average yield potential of spring wheat is more than 4 Mg ha$^{-1}$, the yield of oats 4.5 Mg ha$^{-1}$ and the yield of barley up to 5.0 Mg ha$^{-1}$. A maximum yield among the studied varieties, obtained in variety comparison tests, was 6.5 Mg ha$^{-1}$ for spring wheat, 7.5 Mg ha$^{-1}$ for oats and more than 8.0 Mg ha$^{-1}$ for barley. At the same time, in case of an extremely droughty summer, the yield of spring cereals can be only 1 Mg ha$^{-1}$. The average yield of oilseed rape is 2.0 Mg ha$^{-1}$ and the maximum yield has reached 3–3.5 Mg ha$^{-1}$; however, the risk of yield failure due to plant pests is relatively high. Taking into account the existing level of production and weighing it against the level estimated from variety comparison tests, it appears that only ~40–50% of the real yield potential of cereals is realised at present. In case of oilseed rape, the utilisation of the yield potential is 60–65%.

At the same time, the analysis shows that cereal cultivation is related to extremely high risk due to natural factors, as pedoclimatic conditions affect not only the yield but also its quality. Climatic conditions influence 1,000 kernel mass to a great degree and the other indicators of yield quality which determine the selling price of a grain crop as well as its suitability for use.

The yield of cereals depends mainly on soil fertility, climatic conditions and use of fertilisers (Fig. 2). Increase in the yield of cereals at the expense of soil fertility is about 36–40 kg per point of soil quality. The effect of climatic conditions on the yield of cereals depends on the soil, the species and the variety as well as on fertilisation. Considering different years, climatic conditions in the intensive growth period of plants in Estonia are unstable. The difference in rainfall is up to 3–4-fold and the difference in average air temperatures in the growth period of spring cereals is up to 4°C.
on the soil, the yield of cereals can increase on average 10–99% at the expense of fertilisers. Yet the variation in yields, related to climatic conditions, is 2–4 times higher compared with yield increase at the expense of fertilisation. The low realisation of yield potential is certainly caused by insufficient fertilisation of crops. Of the cereals, 76% were fertilised in 2001–2003, while the average rate of mineral nitrogen was 45 kg ha\(^{-1}\) (Table 1). Fertilisation was more intensive in case of oilseed rape, which has ensured much higher realisation of the yield potential in the current production conditions.

![Fig. 1. Probability (P, %) of the yield and 1,000 kernel weight of cereals in variety comparison tests (I) and in farming (II) conditions (national average).](image)

![Fig. 2. Probability (P, %) of the barley yield depending on soil quality points without (A) and with agronomically effective (B) fertilisation.](image)

Table 1. Use of mineral fertilisers in Estonia, 2001–2003.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Nutrient, kg ha(^{-1})</th>
<th>Fertilised area, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals and grain legumes</td>
<td>N 45</td>
<td>P 5</td>
</tr>
<tr>
<td>Oilseed rape</td>
<td>N 66</td>
<td>P 10</td>
</tr>
</tbody>
</table>

At the same time, average fertiliser rates for oilseed rape are environment friendly and in concordance with legal restrictions. Use of inputs at an optimum level guarantees higher agronomic efficiency and minimises nutrient emission, calculated per unit yield, into the ambient environment (Kirchmann & Thordvaldsson, 2000). The consequence of the inadequate application of fertilisers was a negative soil nutrient balance in the last decade (Roostalu, 2001; Kärblane et al., 2002), which will result in a reduction in soil fertility and will also inhibit the efficiency of crop production in the long run.

As an average of the FADN farms, the yield of wheat in 2000–2003 was 2.3, the yield of barley 2.0, the yield of oats 1.9 and the yield of rape 1.7 Mg ha\(^{-1}\). Compared with the national average, productivity was 15–20% higher for cereals and 6% higher for oilseed rape. Farm size and yield were not significantly correlated. Variability of the yield among different farms was extremely high (coefficient of variation 31–37%).
This can be partly explained by the level of production costs. The yield of cereals and oilseed rape depends on the level of total and specific costs (r = 0.32–0.39; P < 0.01). Thus producers who use more inputs usually achieve higher agronomic efficiency. As the database of FADN lacks data of the quality of arable land, it does not allow assess the effect of soil fertility. For the study period inter-year differences in the yield were insignificant. Maximum yield was 5.6 for wheat, 5.1 for barley and 3.2 Mg ha$^{-1}$ for oilseed rape. However, in case of only 10% of the producers, the yields of these crops were higher than 3.8, 3.5 and 2.3 Mg ha$^{-1}$, respectively. Higher yield ensures profit increase for producers (r = 0.33–0.37; P < 0.01).

The yield affects not only the economic situation of an individual farm but also the national self-sufficiency for cereals. As grain deficit for 2000–2003 was 25%, and to compensate for this, the national average yield of cereals must increase up to ~2.5 Mg ha$^{-1}$. Considering the real yield potential, this would be feasible but only in case producers are economically motivated to intensify production to some degree.

### Income and input structure

Output is directly related to land use structure in farms. Among the cereals, the largest share is accounted for by barley with 25–43% and wheat with 15–29% (Table 2). The share of oilseed rape is on average 20.4%. The share of oilseed rape is smaller in farms with an area less than 100 ha. Depending on the size of the farm, total output is in the range of 3,300–5,350 EEK ha$^{-1}$, from which the share of cereals forms 2,120–3,090 EEK ha$^{-1}$ and the share of oil crops 800–1,760 EEK ha$^{-1}$. The share of oil crops is larger in farms with a larger output (r = 0.52; P < 0.01).

The proportion of subsidies in income made up on average 7.9–11% (Table 2). In Finland the share of subsidies in cereal farms varied from 35 to 53% (Kaljonen, 2006). As European Union Common Agricultural Policy (CAP) was implemented in Estonia as late as 2004, its effect is not reflected in the present results. Taking account of the general trend of the EU policy towards minimisation of subsidies and decoupling of production in the future, the low share of subsidies even gives a better overview of the sustainability of the agricultural sector. Changes in agricultural policy definitely affect grain producers (Ackrill et al., 2001; Fraser, 2005; Chatellier, 2004). Loko et al. (2005) have calculated that when the single area payment is equal for grain and grassland the trend will be to replace grain production with grassland.

As an optimal scale can be established practically over the all range for outputs and inputs, it is difficult determine an efficient scale (Forsund & Hjalmarsson 2004). During four years (2000–2003), total inputs increased 21%. Total inputs were the highest in large farms (Table 2). Average total input was 3,487 EEK ha$^{-1}$, and total specific costs varied between 40–55%, while the share of the former increased 6.8% during four years. Fertilisers accounted for an average of 19.7% and crop protection 9.7% of total inputs. The proportion of depreciation is the highest in small farms and that of wages by large-scale producers. There is strong correlation between the share of wages and farm size (r = 0.95; P < 0.01).

The efficiency of the use of labour depends strongly on farm size. In small farms it is more than two annual work units (AWU) per 100 ha. The most efficient use of labour (0.8–1.0 AWU 100 ha$^{-1}$) occurs in farms with a size range from 175 to 600 ha. Paid labour exceeds unpaid labour in farms with a size over 300 ha (Fig. 3). It is evident that still larger farms are not the so-called family farms any more.
Profitability of grain production

The size of a farm is an important factor which determines its efficiency (Lund & Price 1998). Generally, profitability increases with farm size (Burger, 2001; Gorton et al., 2003). Farm size is often identified according to the area of agricultural land. Optimum farm size is a relative criterion as it is highly dependent on farm type, land use structure and the level of specialisation (Gorton and Davidova, 2004; Alvarez and Arias, 2004). The relationship between farm size and efficiency have been found to be positive (Hallam & Machado, 1996; Hadri & Whittaker, 1999), negative (O’Neill & Matthews, 2001) and also non-linear (Helfand, 2003). This indicates the complexity of identifying optimal farm size.

There were 36,859 operating farms in Estonia in 2003. The farms in possession of legal persons numbered 783. The average area of a farm was 21.5 hectares. Despite small average farm size, farms larger than 50 ha accounted for as much as 66% of all agricultural land. Grain producers of farms of this size use as much as 81% of all subsidised land. Grain production subsidies were applied by 4,284 producers for 286,619 ha; proceeding from these figures, average cereal growth area per farm is 68 ha. As an average for 2000–2003 and according to the FADN database, grain producers were profitable in all size groups (Table 1; Fig. 4A). Average farm family income (FFI) was 1,376 EEK ha⁻¹. There is a non-linear relationship between farm size and economic indicators. FFI increases up to ~400 ha. The increase is most significant in the size range 40–200 ha where the increase in farm size by one hectare increases FFI by 7.6 EEK ha⁻¹. Further increase will decelerate profit and the most efficient use of labour occurs in this size range as well. Cost benefit is the highest (>50%) for farm size ranging from ~150 to 400 ha. FFI is negatively correlated with the labour used per 100 ha (r = -0.27; P < 0.01) and with costs for wages (r = -0.30; P < 0.01) and positively correlated with the output of oil crops (r = 0.40; P < 0.01), which indicates higher profitability of rape production compared to cereal production. Use of labour and its estimation in a farm markedly affects the cost benefit of production.
for paid labour were on average 3,053 EEK ha\(^{-1}\) per month. As the present low level of wages in the agricultural sector increases in the near future, optimum use of labour will affect even more the competitive ability of grain producers.

The lowest limit of the profitable size of FADN farms coincides with the theoretical calculations of the breakeven size of grain farms. Möller et al. (1998) have found that maximum cost benefit is guaranteed for a grain farm with sowing acreage from 78 to 95 ha. Lower cost benefit in FADN farms larger than 600 ha is mainly related to higher labour costs.

Yield of grains was positively correlated with profit \((r = 0.33 \text{ – } 0.37; P < 0.01)\), while correlation was weaker with cost benefit \((r = 0.16\text{ – }0.22; P < 0.01)\). Consequently, increasing costs increase yield less than would be required for attaining economic efficiency. Cost benefit is reduced by increase in total costs \((r = -0.24; P < 0.01)\) and costs of wages \((r = -0.34; P < 0.01)\). There is no correlation between the level of specific costs and cost benefit, which gives evidence of the incorrect ratio of inputs to selling price of production, or of the low efficiency of inputs.

**CONCLUSIONS**

Decreased production and low agronomical efficiency have induced a situation where Estonia is unable to ensure self-sufficiency for cereals. The low realisation of yield potential at national level is partly caused by insufficient fertilisation. In FADN farms agronomical efficiency is somewhat higher compared with the national average but grain yield differs to a great extent between farms. The European Union Common Agricultural Policy was implemented in Estonia as late as 2004, and for that reason the share of subsidies in income of grain farms in 2000–2003 was low. Further it is crucial to analyse how EU support schemes have affected the economic situation of grain producers. The estimation of economic sustainability should be improved with a Stochastic Frontier Analysis and Data Envelopment Analysis. Those methods have been widely used for determination of farm efficiencies in transitional economies (Fandel, 2003; Lattrouf et al., 2004) but not in Estonia so far. Although FADN grain farms were profitable in all size groups, the profitability was highest in the size range from ~150 to 400 ha. Use of labour and its estimation markedly affects the cost benefit of production. Consideration of total labour costs indicates that small grain farms are unprofitable.

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The effect of potassium and phosphorus fertilizers on the potato yield depending on pedoclimatic conditions


**THE EFFECT OF POTASSIUM AND PHOSPHORUS FERTILIZERS ON POTATO YIELD DEPENDING ON PEDOClimATIC CONDITIONS.**

ProCeedings of the Latvia University of Agriculture 8: 33–37.

**Abstract.** On potassium poor soils, the average effectiveness of K₂O fertilizer norm is 60-80 kg of tubers per kg of K₂O, while in favorable years it can be as high as 120-140 kg. On soils with lactate solvable potassium below 130 mg K₂O kg⁻¹, moderate amounts of potassium fertilizers provide a yield increase of potato almost every year. On soils with very high potassium content, potassium fertilizers ensure yield increase only in one to three years out of ten. An increase in soil potassium content by 10 mg K₂O kg⁻¹ decreased the average effectiveness of the K₂O rate by 5.5 kg of tubers per 1 kg of K₂O applied. Phosphorus fertilizers produce a positive effect every other year on soils with the lactate solvable P₂O₅ content below 200 mg kg⁻¹. On phosphorus poor soils (below 70 mg kg⁻¹), the effect of phosphorus fertilizers is evident almost every year, and the effectiveness of the use of low phosphorus amounts (P₂O₅) is on average higher than 50 kg of tubers per kg P₂O₅. The increase of plant available phosphorus in soil by 10 mg kg⁻¹ results in reduction of P₂O₅ use by 3.2 kg of tubers on average per 1 kg of P₂O₅ applied.

**Key words:** PK fertilizers and balance, potatoes, profitability of fertilization.
The effect of potassium and phosphorus fertilizers on the potato yield

22%, while the content of lactose soluble phosphorus increased by 9%, during this period.

During the period of Estonia's re-independence, the balance of all main nutrient elements has become negative as a consequence of inadequate fertilization. The average amounts removed from the soil with the yield were 55 kg N, 21 kg P₂O₅, and 54 kg K₂O, while the amounts returned to the soil—30 kg N, 11 kg P₂O₅, and 18 kg K₂O. Thus the present production takes place largely at the expense of the soil resources created by farmers in the 1970s-1990s. The content of soil lactate soluble potassium of Estonian arable land is low for 43.4%, moderate for 42.5%, and high for 14.0% of soils. The content of lactate soluble phosphorus is very low or low for 28.9%, moderate for 46.8% and high or very high for 24.3% of soils (Jarvan et al., 1996).

In the case of general balance of potassium and phosphorus, it is necessary to take into account that in the first year plants utilize only certain part of available nutrients. Among mineral fertilizers, plants utilize 50-70% of potassium in the first year and with a total of 70-80%. Assimilation of phosphorus from superphosphate varies from 10 to 30% in the first year of application, while the amount assimilated from manure is 20-40%, with a total of 25-45% and 40-60% per rotation, respectively. Utilization of potassium and phosphorus from soil resources depends on the crop, and even more on the content of nutrient elements available in the soil. In the case of a very low content of soil nutrient elements, the plants are able to utilize 8-26% of phosphorus resources and 15-90% of potassium resources. Thus, considering our current application of potassium and phosphorus fertilizers, it can be supposed that the active balance of these nutrient elements is significantly more negative than reflected by their total balance.

Methods and materials

The present study summarizes the results of previous fertilization experiments conducted with potato (Aamisp, 1939; Estriõnundastetg, 1946; Õunast, 1946; Taltsunnast, 1966, 1969, 1970; Vilinast, 1966; Suter, 1967; Sirend, 1969; Tartast, 1969; Sepp, 1972, 1974, 1978; Põkio, 1971, 1973, 1977, 1978; Kiirlaan and Tartian, 1989; Valsan, 1992), as well as analyses of crop response to the application of the potassium and phosphorus fertilizers and related agroeconomic risk factors. The database, which contains the results of more than 250 field experiments performed in Estonia with medium- or late-maturing potato varieties, was used. These experiments have been carried out on soils with very different texture and other properties. The impact of soil and climatic conditions on the effectiveness of fertilizers has been assessed according to the theory of probability.

The assessment is based on regression analysis, which has the following general form of the equation:

\[ y = a_0 + a_1 x + a_2 P_k + a_3 P_j + a_4 P_u, \]

where \( y \) — average effectiveness of fertilizer rate \( P_k \) or \( P_j \) per kg K₂O or P₂O₅ kg⁻¹;

\( x \) — lactate soluble K₂O or P₂O₅ content in soil, mg kg⁻¹;

\( P_u \) — probability, %.

In the calculation of the probability of fertilization (Ry, %) it was assumed that the commercial yield (60% from total) is sold at 1.5 EK during the year, but the rest of the yield is converted to milk or pork, the selling price of which is 3.0 and 20 EK kg⁻¹, respectively. The cost of fertilizers is 3.3 EK kg⁻¹ for K₂O and 10.9 EK kg⁻¹ for P₂O₅. The cost of harvesting is 0.2 EK kg⁻¹. The feeding of animals proceeds from a balanced feed ration and the calculation of the requirement for metabolizable energy and protein was based on the requirement for purchased concentrated fodder and its cost.

Results and discussion

The effectiveness of potassium fertilizers to a great extent depends on soil potassium level, use of the nitrogen and phosphorus fertilizers and manure, and the crop specific, and also on climatic conditions during the potato growth period (Fig. 1). For a longer period average, the effectiveness of fertilizer rate is for potatoes, compared with NP background on soils with very low and low content of available potassium, is 60 to 80% of tubers per kg of K₂O applied. However, in one favorable year out of ten it may even reach 120 to 140 kg of tubers per kg K₂O applied. On soils with moderate and high potassium content, average effectiveness was 2050 kg μK₂O kg⁻¹, but in 2 years out of ten, fertilizer use may not increase the yield of potato. On soils with very high potassium content, the probability of yield increase, which will pay back the expenses of potassium use, is low — 30-60%. If only potassium fertilizers are applied on the background of manure, their effectiveness remains considerably lower. According to Põkio (1973), the effectiveness of potassium fertilizers higher than average can be expected if the summer is relatively cool, but agronomically effective fertilizer rate is 60 to 200 kg of K₂O ha⁻¹, which may vary more than two times depending on the weather conditions.

![Fig. 1. Probability of the average effectiveness and profitability of potassium fertilizer rate K₉₀ depending on soil lactate soluble K₂O content.](image1)

![Fig. 2. Probability of the average effectiveness and profitability of phosphorus fertilizer rate P₉₀ depending on soil lactate soluble P₂O₅ content.](image2)
Conclusion
The complex analysis of the results of fertilization experiments allowed determining the impact of natural and economic risk factors on the effectiveness of fertilization. The higher is the soil nutrient content, the lower are the effective application rates of fertilizers and agroecnologically and economically grounded application rates of fertilizers. The difference in the effectiveness of potassium fertilizers (K₂O) between favorable and unfavorable years can be as high as 80-90% of K₂O kg⁻¹, that of phosphorus fertilizers (P₂O₅) up to 90-100% of P₂O₅ kg⁻¹. The profitability of fertilization depends primarily on effective fertilization and also on such economic risk factors as the cost of fertilizers, the crop related to the management of yield increase as well as sales income. On soils with high potassium and phosphorus requirement, the profitability of the application of fertilizers varies between the 140-170% range. But in the case of lactate soluble potassium- and phosphorus-rich soils, considerable profit from fertilization can be obtained in less than two or three years out of ten.

Acknowledgements
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Anotacii
Augenes ar zemu kaliajā nodrošinājumu, lietot 60 g kg⁻¹ K₂O līdz, tiek samazināts elektivitāte saisma; 60-80 kg bumbujo uz katru ar mēslojumu līmantoja K₂O kāroga. Labvēlīgākais gadījumā tiek ražots mēsloja, ja saisma un realizācijas gadījumā izmantoja 60-90% bumbujo uz katru mēslojumu, tām mēslojumu mēslojumu normas gandrīz ūdu gads nosodina kartupeļu ražu pieaugumu. Palielinot augenes kaliajā nodrošinājumu, pakāpeniski samazinās stāvokļa iznākot kraujām. Praktiskās lidzkadieties atvērties no fosfora mēslojumiem var ietekmēt, taču tās atvērtis var izšķirt augēm un 10% 70 000 kg.12
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