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Phosphorus Application Strategies in Potato

- Constraints and potential improvements

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Sustainable Phosphorus Application Strategies in Potato

Abstract

Phosphorus (P) is an essential element that plays an important role in carbohydrate metabolism and energy transfer systems in all plants. Sufficient P supply is therefore essential for providing adequate food, fibre and fuel for society. In potato, P deficiency reduces yield and tuber number due to reduced radiation interception by the canopy.

Phosphorus is a limited, non-renewable resource. When lost to water bodies, P causes environmental problems such as eutrophication. Potato fields may be a significant contributor to P loads to water due to high P recommendations and a tendency for P leaching in soils where the P sorption/binding capacity is saturated. Efficient use of P in potato cultivation is therefore crucial in order to reduce P consumption and environmental impacts.

The thesis improves the current understanding of potato P requirements as regards optimising P application strategies, use efficiency and potato tuber yield. The results show that split P applications can improve P recovery by 25%, particularly on soils with low P content and low buffering capacity, and can improve physiological P use efficiency (PPUE) where P availability is limiting yield. Irrigation and subsoiling can both significantly improve P recovery, PPUE and yield. Foliar application does not improve PPUE, but can increase P concentration and yield if the plant is supplied with sufficient water. However, foliar P application should not be used as a general strategy, but can be recommended where the soil buffering capacity is extremely high. It is shown in this thesis that many Swedish soils contain sufficient amounts of P to support optimal growth and are no longer responsive to P fertilization. To determine the responsiveness of potato yields to P, data on soil organic material, pH, soil buffering capacity and varietal characteristics are needed, in addition to the amount of P-extractable with ammonium lactate (P-AL value) used in Sweden today. More sophisticated P recommendation models which take these parameters into account are urgently needed. As long as yield effects from P fertilization cannot be predicted, excessive P fertilization will probably continue, resulting in waste of a non-renewable resource, eutrophication of the aquatic environment and reduced farm profits. The findings in this thesis contribute to understanding the complex picture of P acquisition in potato and, hopefully, to more efficient use of the non-renewable P resource.

Keywords: Inter-row subsoiling, irrigation, starch yield, phosphorus use efficiency, foliar fertilization, phosphate, P-AL, buffering capacity, sorption, *Solanum tuberosum*.

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Dedication

To all potato growers in Sweden

The difference between stupidity and genius is that genius has its limits.
Albert Einstein

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Ekelöf, J., Asp, H. & Jensen, E.S. (2012). Potato yield response to foliar application of phosphorus as affected by soil moisture and available soil phosphorus. *Acta Agriculturae Scandinavica, Section B Soil Science* 67(7), 637-643.

II Ekelöf J., Lundell, J., Asp, H. & Jensen E.S. (2014). Recovery of phosphorus fertilizer in potato as affected by application strategy and soil type. *J. Plant Nutr. Soil Sci.* 177, 369-377.

III Ekelöf, J., Gauman, V., Jensen, E.S. & Persson, P. Increase of starch-potato yield, phosphorus use efficiency and quality parameters by inter-row subsoiling and irrigation. *Potato Research* (accepted for publication).

IV Ekelöf, J., Jensen, E.S. & Asp, H. Effects of phosphorus fertilizers on yield and quality in Swedish potato cultivation – An inventory (manuscript).

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The contribution of Joakim Ekelöf (JE) to the papers included in this thesis was as follows:

I Developed and formulated the research question and wrote the application for funding. Planned and carried out the experiment and evaluated the data. Drafted the manuscript and subsequently developed it together with the co-authors.

II Developed and formulated the research question and wrote the application for funding. Planned and carried out the experiment together with the co-authors. Evaluated the data and drafted the manuscript in collaboration with the co-authors.

III Planned and performed the field experiment, with most of the practical management carried out by HS-Kristianstad. Evaluated the data and drafted the manuscript together with V. Gauman and subsequently developed it together with the co-authors.

IV Developed and formulated the research question and wrote the application for funding. Planned the experiment, evaluated the data and wrote the manuscript in collaboration with the co-authors. Most of the practical management of the field experiments was carried out by the farmers, advisory services and technical assistants.

Abbreviations

A0	Phosphorus acquisition in non P-fertilized plots
A1	Phosphorus acquisition in P-fertilized plots
ATP	Adenosine tri-phosphate
BC	Buffering capacity
d.a.e	Days after emergence
DM	Dry matter
DNA	Deoxyribonucleic acid
DWY	Dry weight yield
IFDC	International Fertilizer Development Centre
OX	Acid oxalate
P	Phosphorus
P-AL	Ammonium lactate-extractable phosphorus
PR	Fertilizer phosphorus acquired by the crop
PS	Amount of phosphorus supplied
PU	Total amount of P acquired by the crop
PPUE	Physiological phosphorus use efficiency
PUE	Phosphorus use efficiency
RNA	Ribonucleic acid
Xm	Estimated buffering capacity
Y0	Yield in non P-fertilized plots
Y1	Yield in P-fertilized plots

1 Background

1.1 Phosphorus as a resource

1.1.1 Phosphorus global reserves

Phosphorus fertilizers are produced from mined phosphate rock. The phosphate rock reserves in the world are estimated to be around 67 000 Tg (Jasinski, 2013). However, only 16 000 Tg have the appropriate quality for making suitable products and can be economically processed (Butusov & Jernelöv, 2013). With an annual phosphate rock mining rate of roughly 200 Tg per year, the reserves should last for the next 80 years. If all reserves, including all 67 000 Tg, are included in the calculations, the reserves will last for some 350 more years. However, increasing demand, due to growth of the world population, may speed up the depletion. The annual mining rate is estimated to reach approximately 250-280 million tons per year by the middle of this century (Mew, 2011).

The majority of the world phosphate rock mined in 2013 was from China (~40%), USA (~13%) and Morocco (~13%) (Jasinski, 2013). The phosphate rock reserves in China and USA are scarce and are estimated to be depleted in less than 60 years (Butusov & Jernelöv, 2013). The largest reserves by far are found in Morocco, which has more than 77-85% of the world's phosphate rock reserves (Jasinski, 2013; Science Communication Unit, 2013).

1.1.2 Peak phosphorus

There is an ongoing debate on whether the production of phosphorus will peak (Peak Phosphorus) according to the Hubert curve, as for oil, within this century (Butusov & Jernelöv, 2013; Scholz *et al.*, 2013; Mew, 2011; Cordell *et al.*, 2009). The different scenarios are basically dependent on the quantity and quality of the remaining phosphate rock reserves, which are difficult to determine. The estimated world phosphorus reserves increased from 15 000 Tg in 2008 to 71 000 Tg in 2011 (Jasinski, 2013; Van Kauwenbergh, 2010). The major contributor to this increase was Morocco/Western Sahara, which increased its output from 5 700 to 51 000 Tg. Complete depletion of the phosphorus reserves in the near or mid-term future is therefore unlikely. However, the fertilizer costs will probably increase as less pure and less concentrated ores have to be mined (Butusov & Jernelöv, 2013). No matter how much phosphate rock that exists, phosphorus is a non-renewable resource which causes environmental problems when it reaches watersheds and oceans. Therefore, phosphate fertilizers need to be used efficiently.

1.1.3 Phosphorus fertilizer use in Sweden

Approximately 11 000 tons of inorganic fertilizer phosphorus (P) are imported to Sweden each year (Statistics, 2012). Most of the P in complex fertilizers such as NPK (different concentrations of the components nitrogen, phosphorus and potassium) used in potato cultivation in Sweden is mined in Finland (G. Frostgård, pers. comm. 2013). Finnish P resources are particularly low in cadmium (Cd) compared with other sources. Swedish P fertilizers contained on average 5.7 mg Cd kg^{-1} in 2011, which is 10-fold less than 15 years ago (Statistics, 2012). Other PK products available in Sweden often derive from Russian reserves, which are also low in Cd (G. Frostgård, pers. comm. 2013). In Europe, most inorganic P fertilizer is from Morocco and contains >50 mg Cd kg^{-1} (Butusov & Jernelöv, 2013; Schröder *et al.*, 2010). In order to avoid enriching arable soil with Cd from fertilizer, the concentration should not exceed 10 mg Cd kg^{-1} based on an application rate of 22 kg P ha^{-1} yr^{-1} (Eriksson, 2009).

Swedish agriculture has a large surplus (12 600 tons) in its P balance and P is accumulating in soils. This is mainly due to high P imports in feeds and food. The greatest accumulation can therefore be seen on farms with many animals per unit of land (Linderholm *et al.*, 2012).

1.2 Environmental issues related to phosphorus

1.2.1 Sources of phosphorus losses from soils

The P leaching potential of mineral soils is generally considered to be low (0.1-4 kg ha^{-1} $year^{-1}$) due to high retention capacity (Bergström *et al.*, 2007). However, P losses from agricultural soils occur in practice and cause serious problems with eutrophication (Bergström *et al.*, 2007; Hart *et al.*, 2004b; Tunney *et al.*, 1997). The amount of P lost to waters from agricultural land is often correlated to soil P levels (Tunney *et al.*, 1997). The main processes for P losses from agricultural soils to surface waters are erosion, surface runoff and subsurface transfer. Erosion and surface runoff are mainly a problem in hilly areas, where major P losses can occur (Bergström *et al.*, 2007; Sims & Sharpley, 2005). Subsurface P leaching may occur where water moves by mass flow in soil cracks, *e.g.* in clay soils during dry periods, or in highly fertilized sandy soils (*i.e.* soils commonly used for potato cultivation) with low P sorption capacity and a shallow watertable (Börling, 2003). The widespread use of irrigation together with high P recommendations make potato one of the crops with the highest leaching potential (Chien *et al.*, 2011; Mattingly, 1970; Ozanne *et al.*, 1961).

1.2.2 Issues related to phosphorus losses

The environmental significance of P lies in its dominant role in the eutrophication of aquatic ecosystems, where P is regarded as the limiting nutrient for primary production. When the P concentration in freshwater ecosystems rises and climate conditions are favourable, excessive growth of algae and plankton occurs. After their lifetime, these organisms sink to the bottom and decompose in a process that consumes oxygen and depletes the deeper waters of oxygen, causing the death of fish and other organisms. The contribution of agriculture to the total P loads to waters is estimated to be approximately 30-50% in Sweden (Bergström *et al.*, 2007; Börling *et al.*, 2001).

1.3 Phosphorus in soils

1.3.1 Forms of soil phosphorus

Phosphorus can be present in organic or inorganic form in soils. In most agricultural soils, 30-60% of the P is present in inorganic form, although this fraction can vary from 5-95%. Phosphorus availability is controlled by solubilization and precipitation of phosphate in inorganic form and through mineralization and immobilization of the organic fraction (Shen *et al.*, 2011; Sims & Sharpley, 2005).

The primary inorganic form of P is apatite, with the basic formula $M10(PO_4)6X_2$. The mineral (M) is commonly Ca and less often Al or Fe, while the X represents F^-,Cl^-, OH^- or CO_3^{2-}. Apatite is found in crystalline Al and Fe compounds in acid soils and associated with Ca compounds in alkaline, calcareous soils (Arai & Sparks, 2007). The chemical weathering of inorganic P results in the release of plant-available orthophosphate (HPO_4^{2-} and $H_2PO_4^-$). This reaction is slow and very little plant-available P derived from this source is present in the soil solution at any time (Sims & Sharpley, 2005). Most forms of organically bound P cannot be absorbed into cells and is not available to plants. For cellular uptake to occur, P must first be released from the organic molecule through mineralization. Thus, much of the P used by plants, other than that from applied fertilizers, is believed to come from organic phosphate release by decomposition of organic matter (Shen *et al.*, 2011). Organic P forms include both relatively labile pools such as phospholipids and nucleic acids and more resistant pools such as humic acids.

1.3.2 Microbial transformation of organic phosphorus

Soil organisms are closely involved in the cycling of soil P (Figure 1). Microorganisms have a significant function in the distribution of P between various inorganic and organic fractions and consequently affect the availability of phosphate for plant acquisition (Shen *et al.*, 2011). Organically bound P is released during the mineralization process through the action of phosphatase enzymes. These enzymes are produced by approximately 70-80% of the microbial population, including bacteria such as *Bacillus megaterium* and *Steptomyces* spp., the fungus *Penicillium* spp. *etc*. (Sylvia *et al.*, 2005). Experiments by Covarrubias-Ramírez *et al.* (2005) showed that the use of *Bacillus subtilis* can promote P uptake kinetics and enhance growth of potato.

Once mineralized, P can be taken up by plants, immobilized by the microbial biomass, precipitated in organic complexes or adsorbed to mineral surfaces. Therefore, plants have to compete for available P. The ability of plants to compete varies not only between species, but also between varieties (Trehan & Sharma, 2003; Jenkins & Ali, 2000).

Microorganisms are closely associated with plant roots in the rhizosphere. The capacity of rhizosphere microorganisms (in particular arbuscular mycorrhizal fungi) to increase P availability and plant P uptake is most important in low P soils. It has been shown that mycorrhizae can improve P uptake in potato (Bayrami *et al.*, 2012). Inventories in Sweden have shown that mycorrhizal associations with potato roots seldom occur (Ohlsson *et al.*, 2011). This might be due to the generally high soil P status and intensive use of fungicides in Sweden. However, studies in Iran have shown that soil inoculation with mycorrhizae has the potential to increase yield, even on soils with high amounts of available P (Douds *et al.*, 2007).

Microorganisms may function as a buffer against P losses by accumulating (immobilizing) P from temporally high concentrations in the soil solution (Sylvia *et al.*, 2005). The extent of immobilization is affected by the C:P ratio of the organic materials being decomposed and the amount of available P in solution. Generally, a C:P ratio lower than 200 will result in net mineralization and a C:P ratio higher than 300 in net immobilization.

1.3.3 Fertilizer conversion in soils

Phosphorus in fertilizer added to the soil dissolves into dihydrogen or hydrogen phosphate ions ($H_2PO_4^-$ or HPO_4^{2-}), which start to react with the surrounding soil. In most soils, iron (Fe), aluminium (Al) and calcium (Ca) ions are present and react with the dissolved fertilizer (Arai & Sparks, 2007). The phosphate forms complexes (adsorbs) such as Fe-, Al- and/or Ca- complexes in the water surrounding the granule. The remainder of the fertilizer, monocalcium phosphate ($CaH_4P_2O_8$), is converted into dicalcium phosphate ($CaHPO_4$). Initially the adsorption of P is readily reversible and P is available for plant acquisition or mobilization of microorganisms. The solubility of these newly formed phosphates is reflected in the phosphate concentration in the soil solution. High concentrations of phosphate occur close to the granule, but the ions are spread quite rapidly in the soil solution. Due to the diffusion gradient, P moves away from the granule and the inorganic ions are adsorbed and immobilized from the soil solution to the soil particle surface, leaving hardly any (<1 kg P ha^{-1}) phosphate in the soil liquid (Butusov & Jernelöv, 2013; Sims & Sharpley, 2005). If the concentration drops in the soil liquid due to plant consumption, immobilization or leaching of phosphate, ions can be released and replenish the deficiency in the soil water.

The sorption process also involves a third step where P ions are captured in soil particles and aggregates. This occurs over time as P ions diffuse into the soil particles and become less available to plants. The phosphate gradually undergoes crystallization, occlusion and bonding to organic materials, which makes the P practically unavailable.

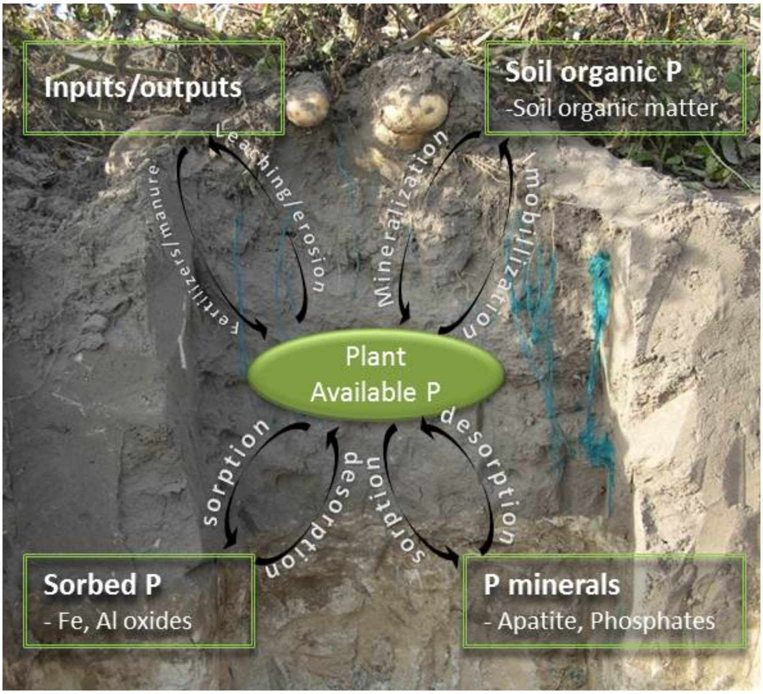

Figure 1. The soil P cycle.

1.3.4 Theoretical concept of critical value

It has been argued recently that the soil P status should be kept close to the 'critical value' (Figure 2). This level is reached when the readily-extractable pool provides most of the plant-accumulated P and P is not yet limiting for yield. In such cases the less available soil P pools are more or less saturated and the P supply can be balanced by crop P removal. Below the critical value, there is a serious risk of loss of yield (Syers *et al.*, 2008), while soil P levels above the critical value result in inefficient P use due to the lack of yield response. In addition, oversaturation with soil P increases the risk of leaching and plant luxury consumption (Sharpley & Menzel, 1987). The concept of critical value optimises the economic returns for the farmer and reduces the risk of P losses to surface waters. In Sweden, the readily-extractable P in the soil is measured as ammonium lactate-extractable soil P (P-AL value; Egnér *et al.*, 1960) (Figure 2).

To determine whether a soil is below or above the critical value, *i.e.* contains sufficient amounts of available P for economically viable yield, an 'omission plot' can be established (Dobermann *et al.*, 2003). An omission plot is a small part of the field where no P is applied and the yield from this plot is compared with that in the rest of the field where P is added. If P limits plant growth, field experiments must determine the amount required.

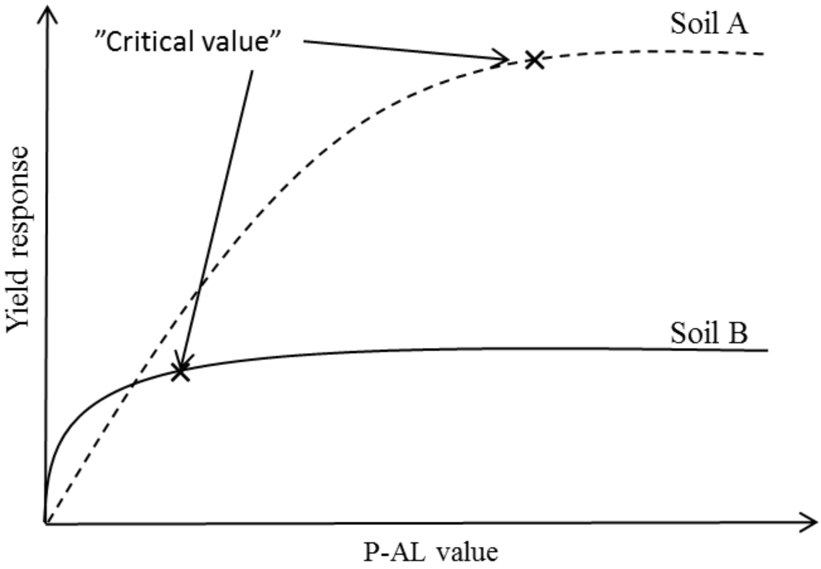

Figure 2. Theoretical concept of the relationship between the ammonium lactate-extractable soil P level (P-AL value; Egnér *et al.*, 1960) and yield. Soil A has a higher buffering capacity and contains more P than soil B. Adapted from Syers *et al.* (2008). The figure illustrates one of the weaknesses with the P-AL method. Soils can be low in P-AL and still be non-responsive to P.

1.3.5 Measuring sorptivity or buffering capacity

Sorptivity or buffering capacity can be described as the ability of the soil to supply (desorb) P to the soil solution. It is a function of the sorption capacity and sorption strength, and controls the rate and amount of desorption. Soils with a high buffering capacity adsorb P strongly and rapidly, making it difficult for plants to acquire sufficient amounts of P. Low soil temperature, low soil moisture and high ionic strength increase the sorptivity (Börling, 2003).

A common way to measure the buffering capacity is to construct isotherms. This is done by measuring the amounts of P that soils sorb at different P addition rates. From the isotherms, sorption indices can be calculated (Hartikainen, 1991; Bache & Williams, 1971). However, this process of determining the buffering capacity by adding different amounts of P is time-consuming. Therefore, simpler methods have been developed to estimate the buffering capacity. Under Swedish soil conditions, the most important sorbents are Fe- and Al-oxides extractable in acid oxalate (Fe_{ox}, AL_{ox}). The buffering capacity (Xm) of Swedish soils can be estimated by the equation (Börling *et al.*, 2001):

$$Xm = 1.29 + 0.69\, Fe_{ox} + 0.109\, Al_{ox}$$

Other factors such as pH, Ca level in the soil, P status of the soil, presence of organic material, fertilizer granule size, fertilizer placement method and climate conditions also influence the sorption process.

1.3.6 Calculating the efficiency of phosphorus use

There are a number of ways of measuring the efficiency of P use in agriculture (Syers et al., 2008). For example, recovery of fertilizer or yield per unit of P supplied. The recovery can be estimated with several different methods:

The direct method: The amount of fertilizer P acquired by the crop (PR), measured by radioisotope analysis, is divided by the total amount of P supplied (PS). This method was used in Paper II in this thesis.

$$\text{Recovery (direct method)} = \frac{PR}{PS}$$

The balance method: The total amount of P acquired by the crop (PU) is divided by the total amount of P supplied (PS). This method is used to evaluate whether P reserves are increasing, decreasing or remaining constant over time. Values lower than 100% calculated with the balance method indicate that more P is being applied than is removed by the crop, and thus soil P reserves are building up.

$$\text{Recovery (balance method)} = \frac{PU}{PS}$$

The difference method: This compares the yield or P acquisition from a non P-fertilized plot with that from a P-fertilized plot. This method can be used in two different ways.

(A) Yield in the non P-fertilized plot (Y0) is subtracted from yield in the P-fertilized plot (Y1) and the result is divided by the total amount of P supplied (PS). This is often referred to as the agronomic efficiency of P.

$$\text{Recovery (difference method A)} = \frac{Y1 - Y0}{PS}$$

(B) P acquisition in the non P-fertilized plot (A0) is subtracted from P acquisition in the P-fertilized plot (A1) and the result is divided by the total amount of P supplied. This is often referred to as the apparent efficiency of P.

$$\text{Recovery (difference method B)} = \frac{A1 - A0}{PS}$$

In this thesis, P use efficiency was defined as dry weight yield (DWY) per unit of P supplied (PS), referred to as the physiological phosphorus use efficiency (PPUE).

$$\text{PPUE} = \frac{\text{DWY}}{\text{PS}}$$

The most appropriate method to use is currently being discussed in the literature (Chien *et al.*, 2012; Selles *et al.*, 2011; Syers *et al.*, 2008). It is also discussed in Paper II and Chapter 5 of this thesis.

1.4 The role of phosphorus in potato cropping

Agriculture and food production are dependent on a P supply to produce adequate food, fibre and fuel for society (Hopkins *et al.*, 2008; Syers *et al.*, 2008). Efficient use of P is also crucial in order to minimize losses of P from agro-ecosystems (Syers *et al.*, 2008; Hart *et al.*, 2004a). The fact that P losses from agriculture contribute to eutrophication of aquatic ecosystems further emphasizes the importance of efficient agronomic P use (Syers *et al.*, 2008; Bergström *et al.*, 2007).

Agricultural land often contains significant amounts of P. For example, Swedish soils often contain about 1500-2000 kg P per hectare (Bertilsson *et al.*, 2005), but most of this P is bound in different complexes in the soil (Rengel & Marschner, 2005). Therefore, P fertilizer needs to be added continuously to sustain optimal plant growth.

Potato is considered a P-demanding crop due to its shallow and relatively short root system (Harris, 1992). Fertilizer P recommendations for potato are therefore higher than for most other crops (Albertsson, 2012; Allison *et al.*, 2001).

1.4.1 Symptoms of phosphorus deficiency

Phosphorus is an essential element which plays an important role in basic plant carbohydrate metabolism and energy transfer systems in potato. It is a part of the structure of DNA, RNA, ATP and phospholipids in membranes. Phosphorus deficiency leads to a general reduction in most metabolic processes, including cell division, cell expansion, respiration and photosynthesis (Marschner, 1995). Chlorophyll and chloroplast formation is less affected than cell and leaf expansion, so the upper side of the leaf becomes a darker green colour. The lower side of the leaf and the stem often turn purple, although it is common to observe yield loss without these symptoms (Bennett, 1993; Hahlin & Ericsson, 1981). Large visual differences occur between potato varieties, and some show purple colouring even though they are not P-deficient. Deficiency symptoms in potatoes can be observed as stunted plants with shortened internodes and poor root systems, which can be seen right from the early stages of growth (Figure 3).

Figure 3. Deficiency of P is difficult to detect in the field. This P-deficient potato plant shows an upright growth pattern and shortened internodes with smaller leaflets compared with the control.

When plants are suffering from P deficiency, a greater proportion of total carbon production is used in root respiration. Therefore, overall top growth is restricted, while root growth is less affected, resulting in an decreased shoot/root ratio (Marschner, 1995). However, tuber set is negatively affected by P deficiency (Grewal *et al.*, 1993; Tukaki & Mahler, 1990).

1.4.2 Mode of action

Grewal *et al.* (1993) reviewed the effect of P in potato and concluded that both height and leaf area index are positively related to P fertilizer application in P-deficient soils. Studies by Jenkins and Ali (1999) showed that yield increases following P application are mainly due to increased radiation interception rather than increased conversion efficiency. This finding is in line with Allison *et al.* (2001), who suggest that increased ground cover and associated increased radiation absorption is the mechanism by which P fertilizer increases yields. Furthermore, Jenkins and Ali (1999) showed that P application mostly enhances early crop development and that the response to P application decreases with time. Treatments receiving insufficient P fertilizer in that study had their optimum interception level delayed by approximately 2-3 weeks, indicating that higher P application rate promotes earlier senescence. Significant yield increases were found at early harvest, but no significant responses for either dry matter production or P uptake were found at final harvest (Jenkins & Ali, 1999).

Experiments by O'Brien *et al.* (1998) showed that number of tubers is positively correlated with light quantity absorbed by the crop during the first week of initiation. Since P fertilization increases the interception of solar radiation in low soil P conditions, it is likely that P fertilization has a positive effect on tuber set in such conditions (Tukaki & Mahler, 1990).

1.4.3 Phosphorus acquisition in potato

Phosphorus is taken up by the potato crop continuously over the growing season. However, the amount taken up per day varies depending on the phenological stage. Although P is crucial, the element is needed in relatively small amounts, 0.5 kg ton^{-1} compared with 3 kg ton^{-1} for N and 4 kg ton^{-1} for K (Stark *et al.*, 2004; Dampney *et al.*, 2002; Bennett, 1993). The highest P uptake rate in foliage and tubers occur during the tuber formation and tuber development stage (Covarrubias-Ramírez *et al.*, 2005). Experiments have shown that the maximum daily P acquisition rate in potato is about 1.4 kg ha^{-1} day^{-1} (Kolbe & Stephan-Beckmann, 1997a; Kolbe & Stephan-Beckmann, 1997b). This highest rate occurs between 30 and 45 days after emergence (d.a.e.). An average daily tuber accumulation rate of 0.155 kg ha^{-1} day^{-1} was observed by Grewal *et al.* (1993) between 30 and 80 d.a.e. After that period, P levels in the shoot continuously decrease until senescence. During the process of senescence, nutrients are relocated from the leaves to the tubers and negative uptake rates of P in the leaves can therefore be observed.

Diffusion is the main mechanism for the movement of P to the root surface. The driving force of diffusion is a concentration gradient. In soil-grown plants, a concentration gradient is formed between the root and the soil surface when uptake rate exceeds the supply by mass flow. In experiments by Bhadoria *et al.* (1991), the diffusion coefficient increased from 0.10 x 10^{-13} to 4.45 x 10^{-13} m^2s^1 as the volumetric soil water content increased from 0.12 to 0.33 g cm^3. Field and greenhouse experiments have shown that low soil water contents and low soil temperature affect P uptake negatively (Sims & Sharpley, 2005; Allison *et al.*, 2001; Marschner, 1995). Harris (1992) reviewed the effect of soil moisture on P availability and concluded that increased volumetric soil water content improved the availability of P to the potato crop. At high soil water content the path length over which P has to diffuse to the root decreases, so lower concentrations of P are needed to maintain diffusive supply (Allison *et al.*, 2001). Root growth has also been shown to increase with increasing soil water content (Marschner, 1995). It is therefore probable that use of irrigation will increase both P availability and the ability of roots to search for P, thus reducing the P fertilizer requirements. The activity of the microorganisms involved in mineralization is also stimulated by high soil moisture content, since many of the organisms in the soil fauna are highly dependent on water in order to function (Sylvia *et al.*, 2005).

1.5 Phosphorus application strategies

Phosphorus fertilizer can be applied in several different ways to the potato crop. It can be banded, broadcast or applied through fertigation or by foliar application. The advantages and disadvantages of each of these strategies are briefly discussed below.

1.5.1 Broadcasting

Broadcasting is the least efficient method from a plant perspective, but the most widely used application method in practice. The availability of high-capacity machinery, which lowers the costs of fertilizer application, is the main reason for the popularity of this strategy. In most cases the fertilizer is spread prior to planting and then incorporated into the ridges by cultivation. However, when the fertilizer is mixed into the soil the fertilizer to soil contact area increases, which results in a high adsorption rate (Sims & Sharpley, 2005).

1.5.2 Placement

Precision placement of P fertilizer near the active root zone (banding) is the most commonly recommended application method. Placement of the fertilizer reduces the contact area with the soil, thus avoiding soil binding (Marschner, 1995). Placement may decrease the P sorption rate, affecting P acquisition positively. This can decrease the P fertilization requirement by approximately 50%. Higher tuber yield can be obtained if the P fertilizer is placed 5 cm to the side of the seed pieces instead of being placed below or mixed into the ridges (Grewal *et al.*, 1993).

1.5.3 Liquid phosphorus fertilizer

Application of P through drip irrigation systems is generally not recommended because of its high clogging potential and limited movement in soil. However, recent studies have shown that P fertilizer use efficiency can be increased by 45% with fertigation compared with broadcasting and by 25% compared with banding. Leaf area index, dry matter accumulation and yield can be increased if P is applied by drip irrigation compared with conventional fertilization techniques (Singh *et al.*, 2004).

1.5.4 Foliar phosphorus application

The acquisition of P through leaves takes place in small (<1 nm) hydrophilic pores within the cuticle. These pores are readily permeable to solutes such as urea (radius 0.44 nm), but not to larger molecules such as chelates (Eichert *et al.*, 1998). The rate at which leaves take up nutrients is dependent on the nutrient status of the plant and the concentration of the liquid applied to the leaf. Climate conditions during acquisition are also important. During the daytime the evaporation coefficient is often higher, resulting in more rapid drying of the spray, which is less favourable for foliar uptake (Alexander, 1986).

Foliar P application is reported to increase tuber number and total yield (Fageria *et al.*, 2009; Grewal *et al.*, 1993). A survey by the British Potato Council showed that about 15% of the potato-growing area in the UK received applications of foliar P in addition to soil-applied P. Corresponding data for Sweden are not available. Application of about 2 kg ha^{-1} is generally recommended when plant P status is low or when potatoes are grown on low P soils. Not all plants are able to acquire P through their leaves, but potato plants have this ability (Marschner, 1995; Prasad & Brereton, 1970).

In order to increase number of tubers, the use of foliar P must increase ground cover and radiation absorption by the time of tuber initiation (Allison *et al.*, 2001). Initiation of tubers usually begins shortly after emergence and is generally completed within 2-6 weeks (O'Brien *et al.*, 1998). Foliar P treatments therefore need to be applied rather soon after plant emergence in order to allow sufficient time to affect the crop ground cover. However, crop ground cover at that time is relatively low (2-32%), and because of that, most foliar P will not be intercepted by the crop canopy but will end up on the soil (Allison *et al.*, 2001).

Allison *et al*. (2001) tested the effects of foliar-applied P on tuber fresh weight (FW) yield and number of tubers in six experiments and found no significant effects on either FW yield or tuber number, despite the fact that two of the experiments were carried out in soils with P index = 0 and all experiments included treatments that had received no soil-applied P fertilizer. Since the results from foliar P experiments seem to vary considerably (Andersson, 2002; Dampney *et al.*, 2002; Johnson & Vaidyanathan, 1993; Kilpatrick, 1993; Berndtsson, 1991; Dawson, 1973), more research is needed to understand the process of P acquisition through the leaves.

1.6 Varietal differences

Potato varieties have different abilities to acquire and utilize P and therefore differ in their P fertilizer requirements (Trehan & Singh, 2013; Balemi & Schenk, 2009; George *et al.*, 2008; Trehan, 2005). The differences may be significant and some varieties may need twice as much P fertilizer as others in order to achieve the same concentration (Trehan, 2005). Biomass partitioning in modern potato varieties is approximately 1% to roots, 15% to shoots, 0% to fruits and 85% to tubers, whereas in wild potato species partitioning is 18% to roots, 52% to shoots, 23% to fruits, and only 7% to tubers (Errebhi *et al.*, 1999). The difference in P utilization efficiency can be explained by several factors, such as size of the root system, efficiency of the root system and internal concentration demand of the plant (Shenoy & Kalagudi, 2005; Dechassa *et al.*, 2003). In order to optimize economic returns and P use efficiency, variety-specific recommendations, as for N, would be appropriate for P. No such recommendations are available in Sweden.

1.7 Effects of subsoiling

Ideal conditions for potatoes are deep, well-drained and loose soil (Pierce & Burpee, 1995). Soil compaction increases the soil resistance and bulk density, which reduces air and water infiltration, resulting in adverse effects on root development and microbial activity (Nawaz *et al.*, 2012; Hamza & Anderson, 2005). When root systems are limited, the volume from which the plant root can extract water and nutrients decreases. Deep cultivation or subsoiling is an effective way of breaking up soil compaction and increasing the yield of several crops (Hamza & Anderson, 2005). It encourages roots to grow below compacted layers, improves moisture infiltration and increases pore volume and macroporosity, resulting in better air movement in the soil (Rolf, 1991; Ide *et al.*, 1984). Due to improved rooting, subsoiling has shown the potential to increase P accumulation in potato tubers (Westermann & Sojka, 1996).

Studies applying artificial compaction have shown that this can decrease potato yield by up to 72%. The yield reduction reported in different studies is on average 18 ton ha^{-1}, but maximum reductions of 25-38 t ha^{-1} have been observed (Stalham *et al.*, 2005; Van Loon *et al.*, 1985; Timm & Flocker, 1966). Thus soil compaction can reduce crop yield and quality and also physically restrict the development of tubers (Batey, 2009; Stalham *et al.*, 2007; Westermann & Sojka, 1996). Sandy soils, in which potatoes are often grown, are highly susceptible to subsoil compaction (Stalham *et al.*, 2005; Westermann & Sojka, 1996; Miller & Martin, 1990).

Potato plants are more sensitive to water stress and soil water fluctuations than most other crops (Jabro *et al.*, 2012; Onder *et al.*, 2005). They require high water availability, with minimum variation in soil moisture content, in order to produce high yield and high tuber quality (Alva *et al.*, 2012). This sensitivity to water stress is most often explained by the relatively shallow root system of the potato plant and by the low root/shoot ratio, which limit its capacity to extract water and nutrients from the soil (Harris, 1992). The roots of most plant species can penetrate compacted soils with soil resistance (Ω) of up to 2-3 MPa, but growth of potato roots begins to be restricted at 1 MPa (Stalham *et al.*, 2007). A survey of 602 commercial fields in the UK showed that two-thirds had Ω greater than 3 MPa in some part of the potential profile for root growth (Stalham *et al.*, 2005). Soil compaction may be one of the main contributing factors to potato sensitivity to water stress.

2 Aim and objectives

The aim of this thesis work was to provide new knowledge on phosphorus application strategies to enhance P use efficiency and yield in potato. Strategies such as split application of P and foliar application, irrigation and subsoiling were tested. The work also included a study of Swedish potato yield and quality effects of P fertilization in farmers' fields. Critical soil parameters for P acquisition were examined. Specific objectives were to:

- determine the tuber yield and P acquisition effects of foliar P application in combination with plant P and water status (Paper I).

- determine whether the recovery efficiency of fertilizer P can be improved by synchronizing P demand and supply, thus avoiding soil adsorption (Paper II).

- evaluate the effects of irrigation and subsoiling on tuber yield and P acquisition (Paper III).

- evaluate the effects of P supply on actual tuber yield and quality in Swedish potato cultivation (Paper IV).

- determine the most important soil parameters influencing the tuber yield response to P fertilizer (Paper IV).

The starting hypotheses tested in Papers I-IV were as follows:

(i) PPUE is improved with foliar application of P (Paper I).
(ii) Split application of P improves recovery of the P supplied (Paper II).
(iii) Subsoiling and irrigation improve PPUE (Paper III).
(iv) Most commercially grown potato crops in Sweden do not respond to P fertilization in a short-term perspective (Paper IV).
(v) Several soil property parameters in addition to P-AL and estimated yield are needed to predict the yield response to P fertilization (Paper IV).

3 Materials and methods

Two of the studies on which this thesis is based were conducted in a controlled environment (Papers I and II) and two were carried out in the field (Papers III and IV). The studies reported in Papers I and II were one-season experiments, Paper III includes data from three experiments in two years (2008 and 2009) and Paper IV is based on data from three years (2009-2011) (Table 1).

Table 1. *Main characteristics of the experiments described in Papers I-IV*

Paper	Year	Soil type/s	Treatment A	Treatment B	Soil P application levels	Harvesting occasions
I	2007	50% (v/v) pumice stone 50% peat	Foliar P	Moist, 0.35-0.45 g water cm^{-3}	0, 72, 155, 222, 300 (mg pot^{-1})	1
			No foliar P	Dry, 0.25-0.35 g water cm^{-3}		
II	2008	Sandy loam, P-AL[a] 4.7, clay content 11%	Split P application		0, 75, 155, 308, 615 (mg pot^{-1})[b]	4
		Silt loam, P-AL 15, clay content 8.5%	All P applied at planting			
III	2008	Sandy loam, P-AL 28, clay content 12%	Subsoiled to 50 cm	Irrigated, 30 kPa	35 kg ha^{-1}	2
	2009	Sandy loam, P-AL 25, clay content 12%	Not subsoiled	Irrigated, 70 kPa		
				Not irrigated		

IV	2009		No fertilizer P	0	1
	2010	Numerous			
	2011		Fertilizer P	Various	

[a]Ammonium lactate-extractable P (Egnér *et al*., 1960)
[b]Applied P was labelled with the radioactive isotope ^{32}P in order to distinguish between soil-derived and fertilizer-derived P. Experiments in a controlled environment

3.1 Experiments in controlled environment

In Papers I and II, potato (*Solanum tuberosum* L., cv. Ditta) plantlets were grown in climate chambers under 18 h daylight at 20°C/18°C (day/night). The humidity was continuously adjusted to 65%, and the fluorescent light intensity was 350 µmol m^{-2} s^{-1}.

3.1.1 Selection of plant material and growing containers

To achieve uniformity, a surplus of plantlets was punched out from one sprouting eye of a seed potato which had been pre-cultivated for 6 weeks. The plantlets were kept for 3 days in humid conditions to allow small roots to form and a protective crust to develop. In commercial fields, approximately 40 000 tubers (plants) are planted per hectare. Each plant forms several sprouts, resulting in approximately 200 000 sprouts per ha^{-1} (Bodin & Svensson, 1996). In Papers I and II, the most uniform plantlets were selected and cultivated in pots (one plantlet per pot) measuring 30 cm in diameter and 22 cm in depth. This is equivalent to approximately 150 000 sprouts per ha^{-1} if calculated by area. The rooting depth in the field is commonly 25-30 cm, which means that the rooting volume in the pot experiments was somewhat restricted.

3.1.2 Water supply

There is generally a large variation in water consumption between plants with different treatments in pot experiments. Each pot was therefore watered individually by weighing once every 5-7 days (Papers I and II). The irrigation was scheduled with tensiometers, which were allowed to reach -40 kPa during the first part of the growing season up to mid-bulking, before distilled water was applied. During late bulking and maturation, the soil was allowed to reach -60 kPa before water was applied (Paper II).

3.1.3 Petiole samples

Petiole samples for nutrient analysis were collected in all experiments included in this thesis. The most recently matured petiole (4th) was analyzed approximately 25 d.a.e.. In the field experiments, 20 petioles from each plot were harvested and in the pot experiments six petioles (one from each plant) per treatment were harvested. The petioles were oven-dried at 70 °C, milled, combusted in nitric acid by means of a microwave technique and analyzed for total P concentration by ICP-AES.

3.1.4 ^{32}P isotope technology

Radioisotope labelling was used in Paper II to distinguish the origin of the plant P content (fertilizer or soil). This was done with the direct method (Kirkby & Johnston, 2008) using the radioactive isotope ^{32}P, which is a high-energy β-emitter. The radioactivity from ^{32}P was measured with a Philips PW4700 Liquid Scintillation Counting (LSC). The emissions were counted by direct detection, *i.e.* without adding the scintillation cocktail (adsorbate), using Čerenkov counting, which measures the β-spectrometry. On each analysis occasion, control samples from S1 stock solutions (with known P content) were prepared and analyzed together with the plant samples in order to correlate the number of disintegrations to the P content. The wavelength of emitted radiation was shifted to partly alleviate problems with yellowish colour of organic compounds.

3.2 Field experiments

3.2.1 Subsoiling

In Paper III, subsoiling was carried out between the ridges (inter-row), after planting but before sprouting, to a depth of 55 cm measured from the bottom of the ridge. Inter-row subsoiling was conducted with an Agrisem Cultiplow (Agrisem International SAS, France) designed to fracture deep, compacted soil layers (see Paper III for more details). A subsoiling pre-study carried out prior to planting to a depth of 35 cm in 2007 inspired this strategy (data not shown in this thesis). Due to re-compaction, minor effects were found on soil resistance and no effects on yield in 2007.

3.2.2 Irrigation

Drip irrigation was used in Paper III, for several reasons. Firstly, this allowed the experiment to be completely randomized. If boom irrigation had been used the individual plots would have had to be much larger, which would have resulted in unrealistic costs for a randomized design. Secondly, the soil moisture could be kept within a narrower range. Thirdly, the drip irrigation was automated and controlled via mobile phone, which gave better flexibility. Fourthly, the plots could be kept relatively small, which brought down the costs.

3.2.3 The phosphorus inventory study

The overall effects of P fertilizers in Swedish potato cultivation were studied by establishing 120 zero P plots (zero-plots) of approximately 50 m^2 each in 120 irrigated commercial potato fields (Paper IV). The zero-plots were compared with control plots (corresponding areas of the commercial field close to the zero-plots) that received P fertilizer according to the specific farmer's practice. The management of this experiment was sub-contracted to either farmers or advisory officers due to the number of sites and the geographical distance. The fields were spread over 1300 km, from Skivarp in southern Sweden to Umeå in the north, and represented most potato-growing districts in Sweden. All the farms were recommended by the advisory services and the farmers were known to be genuinely interested and careful.

3.2.4 Statistical analysis

The data in Papers I-IV were subjected to analysis of variance using the General Linear Model (GLM) procedure of IBM SPSS statistics 20.0 for Windows. The Tukey *post-hoc* test was used to test the differences between the mean values when F tests were significant. A detailed description of the statistical analyses is provided in the individual papers.

4 Results and discussion

4.1 Effect of phosphorus fertilization in Swedish potato cultivation (Paper IV)

The P fertilizer inventory on 120 commercial potato farms throughout Sweden showed that there was no significant difference in yield between fields to which P fertilizer had been added by the farmer and plots in the same fields receiving no P fertilizer (zero-plots) (Paper IV). These results indicate that many soils used for potato cultivation in Sweden supply sufficient P to the potato crop and that excessive amounts of P may have been supplied historically. The average P-AL value in the zero-plots and the control plots, measured 25 d.a.e, was 13.4 and 14.5 respectively. These findings are in line with previous inventories by Gustavsson and Söderström (2006) which showed that a great proportion of the agricultural land in Sweden has P-AL values over 15, and to some extent explains the lack of response to P fertilization. The Swedish recommendation for P supply to potato has been reduced by 40-60% since 2007 (Albertsson, 2012; Albertsson, 2006).

4.2 Variety variability in phosphorus requirement (Paper IV)

Two varieties with different characteristics (King Edward and Saturna) were included in the inventory study (Paper IV). King Edward is a non-determinate table potato variety and Saturna is a relatively determinate variety used for the frying industry. The results showed a significant linear correlation between P concentration in the petiole and yield in King Edward, whereas in Saturna no such correlation was observed (Figure 4). Saturna seems to have a lower optimum for P concentration than King Edward. Such varietal differences have been observed in several other studies (Balemi & Schenk, 2009; George *et al.*, 2008; Trehan, 2005). Altogether, these findings show that variety-specific P recommendations for potato would be appropriate.

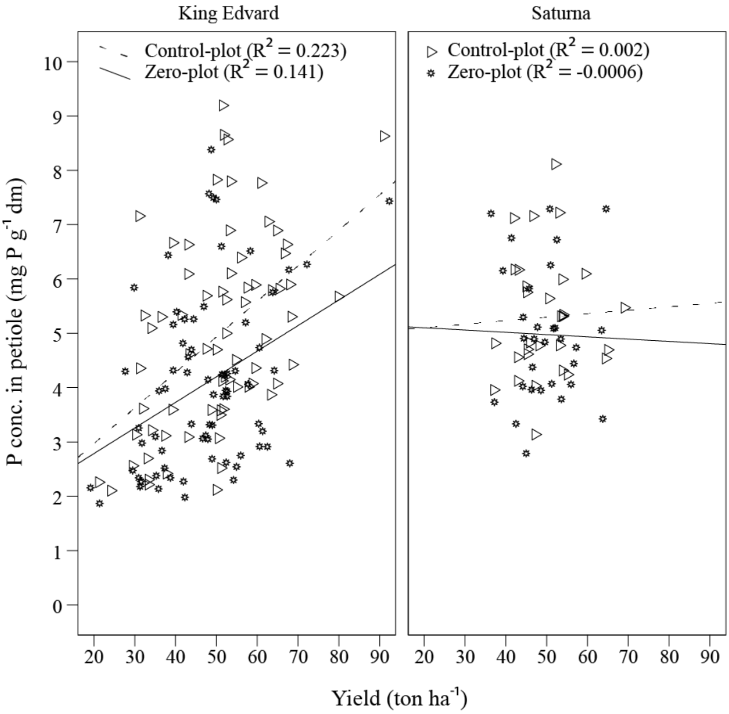

Figure 4. Correlation between potato P concentration in petioles and yield in two cultivars (Paper IV).

4.3 Inputs for new recommendation models (Paper IV)

Step-wise linear regression was carried out in the inventory study to identify critical parameters which could explain the variation in yield and plant P concentration effects due to P supply. A significant yield response of P was observed in fields where petiole P concentration was increased by 1 mg P g^{-1} dm or more (Paper IV). The effect of P fertilizers on petiole P concentration can be estimated using the P-AL (PAL) value, soil organic matter (SOM) content, amount of P applied, pH and buffering capacity:

$$Increase\ in\ petiole\ P\ conc. = 0.142 - 0.002PAL - 0.003SOM - 0.001applied\ P - 0.037pH - 0.002BC\ (adj.R^2 = 0.336, p < 0.05)$$

These results show that soil P content (P-AL) alone is a poor predictor of the variation in yield due to P supply. This finding was supported by the results in Paper II, where the plants grown in the low P soil (P-AL 4.7) acquired significantly more P than the plants grown in the high P soil (P-AL 15), even though the high P soil plants out-yielded those in the low P soil. Several other researchers have pointed out the weakness with recommendation systems based only on soil P extraction (Mohr & Tomasiewicz, 2011; Mattsson *et al.*, 2001; Maier *et al.*, 1989). These results show that there is an urgent need for a new, more complex, recommendation system for P fertilizer supply to potato.

4.4 Factors facilitating phosphorus uptake

4.4.1 Irrigation in relation to phosphorus acquisition (Paper III)

The results in Paper III show that irrigation significantly improves yield, P acquisition and PPUE. The intensive irrigation strategy tested in that study resulted in 14.9% higher starch yield, 4.4% higher P accumulation and 11.9% higher PPUE compared with the unirrigated control treatment. Even larger effects from irrigation were found in a previous one-year field experiment where the interaction between irrigation and P supply was studied (Ekelöf & Råberg, 2011). Zero-P and 50 kg P ha^{-1} were compared under two irrigation regimes, no irrigation and fully irrigated. The results showed that irrigation nearly doubled marketable yield, P recovery and PPUE (Figure 5) (no data except figure 5 is included in this thesis). There are two main explanations for these results. Firstly, the availability of P increases due to an increased diffusion coefficient and a decreased path length over which P has to diffuse to the root (Harris, 1992; Bhadoria *et al.*, 1991). Secondly, irrigation stimulates plant growth, which results in a larger root system and higher yield (Marschner, 1995). Factors that increase P acquisition and yield, such as irrigation, may be the most efficient way to improve PUE in potato.

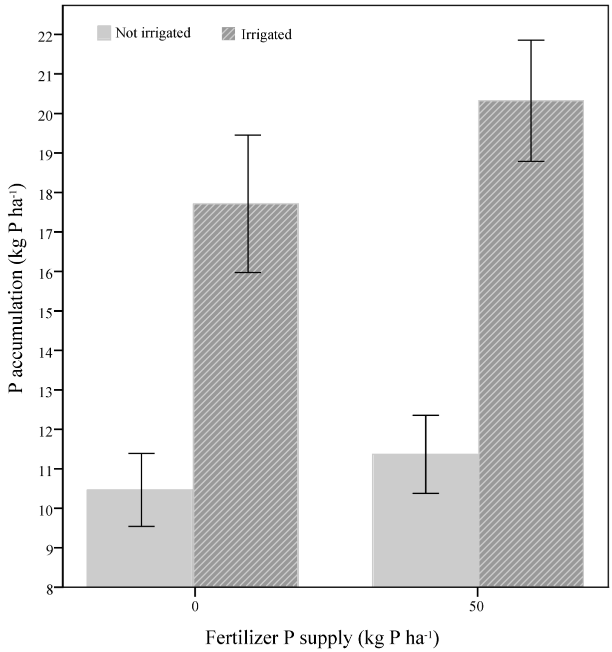

Figure 5. Effects of irrigation and fertilizer application on P accumulation in potato plants with and without P fertilizer supply. Error bars represents 95% confidence interval.

4.4.2 Effects of subsoiling on phosphorus acquisition and yield (Paper III)

The results in Paper III also show that inter-row subsoiling[1] can increase yield and also total P acquisition and PPUE. Starch yield was on average 7.2%, or 1 ton ha^{-1}, higher in the subsoiled treatment than in the untreated plots. Inter-row subsoiling significantly increased PPUE, from 531 to 566 kg DM kg^{-1} P applied or by 6.5%. The P accumulation in the crop was significantly increased, from 30.6 to 32.8 kg P ha^{-1}. Unpublished data from that study showed that only fields with a high sand content (70-90%) in the subsoil should be subsoiled, as otherwise the yield effects could be negative. The yield increase due to inter-row subsoiling observed in Paper III was higher than in many previous studies (Copas *et al.*, 2009; Henriksen *et al.*, 2007; Stalham *et al.*, 2007; Holmstrom & Carter, 2000). For example, approximately 34% of the experiments included in a review by Stalham *et al.* (2005) showed significant yield increases due to subsoiling, 62% showed no response and only 4% of the experiments showed a significant yield reduction. Several factors, such as timing, cultivation depth, choice of loosening equipment and experimental field, may explain the positive results obtained in Paper III. Increased P

1. Loosening of the soil in between the potato ridges

acquisition and yield as a result of inter-row subsoiling was probably due both to greater root to soil surface area and greater access to water and nutrients deep in the profile.

4.5 Phosphorus application strategies

4.5.1 Effects of foliar application on PPUE (Paper I)

Foliar application can increase both dry weight and fresh weight yield (Paper I). However, crop water status is crucial for the effects. No effects of foliar P application were observed if plants were slightly water-stressed (Figure 6). Foliar P application did not affect tuber number and plant P status did not influence the responsiveness of potato to foliar application.

Foliar P application has been suggested to reduce the need for soil-applied P and increase tuber number and total yield (Fageria *et al.*, 2009; Girma *et al.*, 2007; Grewal *et al.*, 1993; Mukherje *et al.*, 1966). However, results from several field experiments over recent decades show that the effects of foliar P application vary considerably, indicating that external factors influence the effects (Andersson, 2002; Dampney *et al.*, 2002; Allison *et al.*, 2001; Johnson & Vaidyanathan, 1993; Kilpatrick, 1993; Berndtsson, 1991; Dawson, 1973). The results from Paper I show that water status of the potato crop can be one explanatory factor for the varying results in the literature. Similar results have been found in experiments with maize seedlings (Yuncai *et al.*, 2008).

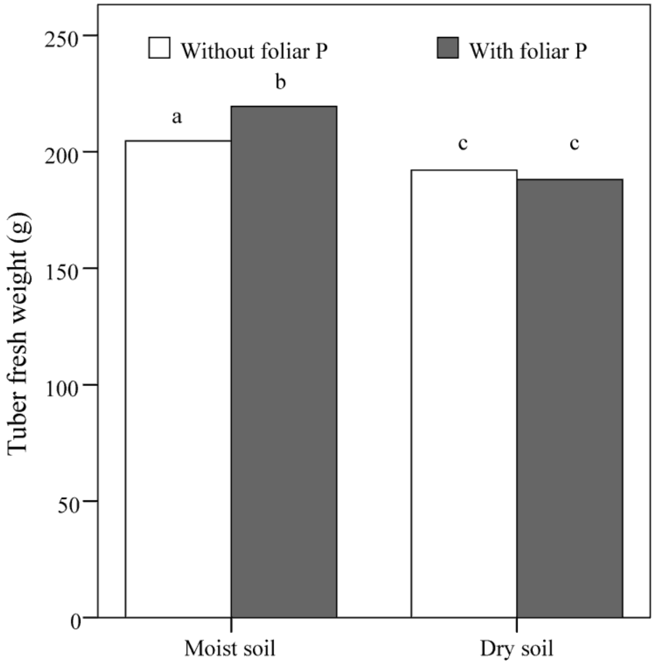

Figure 6. Tuber fresh weight as affected by foliar P application at two soil moisture regimes. The columns represent mean values for soil-applied P. Columns with different letters are significantly ($p<0.05$) different with the LSD test.

In general, foliar application of P resulted in decreased PPUE. This may be explained by the fact that P is taken up less effectively through leaves than through roots, although foliar application may allow more rapid utilization (Fageria *et al.*, 2009). However, there was a significant interaction between foliar application and soil moisture, showing that the PPUE of foliar-treated plant can be maintained if the plants are well supplied with water (Figure 7). Nevertheless, foliar P application should not be considered as a general application strategy, since numerous field experiments have shown no effect (Dampney *et al.*, 2002; Allison *et al.*, 2001).

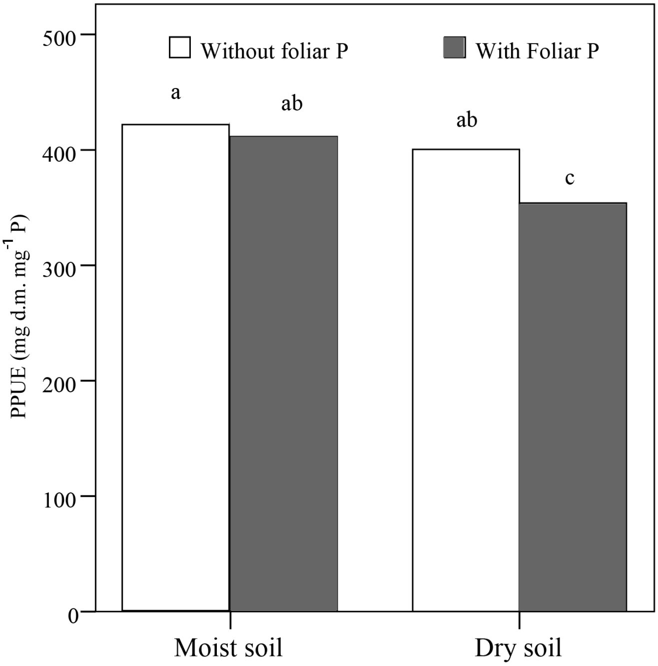

Figure 7. Physiological phosphorus use efficiency (PPUE) as affected by foliar P application and soil moisture. The columns represent mean values for soil-applied P. Columns with different letters are significantly ($p<0.05$) different with the LSD test.

4.5.2 Effects of split application on phosphorus recovery (Paper II)

Phosphorus fertilizers are usually supplied prior to or at planting of potato, even though most P is taken up 40 to 80 d.a.e. (Kolbe & Stephan-Beckmann, 1997a; Kolbe & Stephan-Beckmann, 1997b). This may lead to inefficient P use due to leaching or soil adsorption. Paper II evaluated the effects of applying P multiple times (split application) during the growing period according to plant P requirements. The results showed 25% greater fertilizer recovery when P was applied by split application compared with being applied at planting (Table 2). However, on analyzing the two different soils used in Paper II (high and low P-AL value) separately, only the low P soil with low sorption capacity showed significant results (Figure 8). This may be because of the high sorption capacity, resulting in little or no advantage for the split application strategy in terms of plant-available P. It has been shown previously that fertilizer P can be bound in the soil within minutes or hours of being added to the soil (Pierzynski *et al.*, 2005). Thus, in soils with high sorption capacity, there seems to be no advantage from applying P several times during the growing season. However, in Paper II the phosphorus was applied as a solution, in eight doses, which may have increased the availability and the soil binding rate. In practical potato growing, where granular phosphorus is generally used, binding of P in soil may be slower. Using granules instead of solution may therefore increase the beneficial effects of a split application, even in soils with high buffering capacity.

No significant yield effects were observed for any application level, strategy or soil type. Since the split application strategy only increased P acquisition and not yield, no positive effects were obtained regarding the PPUE. Adding P on several occasions only resulted in luxury consumption in Paper II (Table 2), but in cases where P is restricting plant growth this strategy may increase PPUE.

Table 2. *Average effects of P application strategy (split and single P application) and soil type (low P and high P soil) on dry weight (DW) yield, accumulation of soil-derived P, accumulation of fertilizer-derived P and total accumulation of P. Means within columns assigned different letters are significantly different (*$p<0.05$*) in terms of application strategy (lower case characters) and soil type (capital letters)*

	Total DW yield (g pot^{-1})	Accum. of soil derived P (mg pot^{-1})	Accum. of fert. derived P (mg pot^{-1})	Total accum. of P (mg pot^{-1})
Split	109 a	188 a	43.1 a	232 a
Single	107 a	185 a	34.4 b	220 b
Low P soil	103 A	201 A	52.1 A	253 A
High P soil	113 B	173 B	25.3 B	198 B

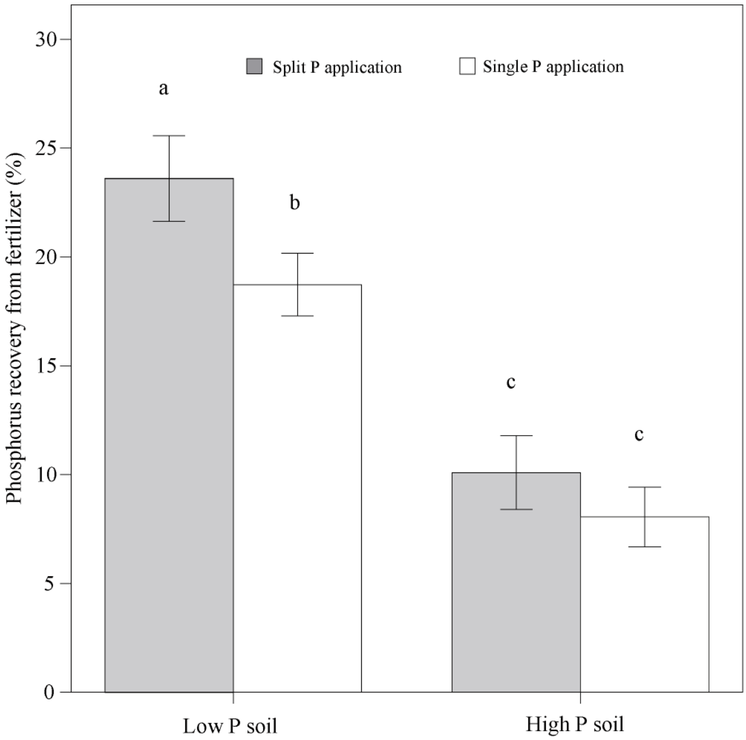

Figure 8. Phosphorus recovery from fertilizer as affected by P application strategy (single and split) and soil P status (high and low). Mean values for all P application levels are included in the diagram. Data shown are for the final harvest at 90 d.a.e. Error bars represent 95% CI.

4.6 Impact of phosphorus fertilizer on PPUE

In Papers I and II, PPUE decreased with increasing P application rate. Similar results were found by Balemi and Schenk (2009), who investigated PPUE in four potato varieties with different efficiencies in two soils with different P levels. The potato yield-response curve to P is steep for the first amount of P acquired and quite flat as the optimum is approached (Paper I). The flat response curve and the high soil P sorptivity compared with other macronutrients explain these results. The PPUE values determined by Balemi and Schenk (2009) were in the range 250-500 mg d.m. mg^{-1} P. The findings in Papers I and II were similar and appear to show that cv. Ditta (used in Papers I and II) is an intermediate P use efficient cultivar.

4.7 Comparing phosphorus use efficiency (Paper II)

Recovery of fertilizer P is sometimes used in the literature to evaluate PUE (Selles *et al.*, 2011; Syers *et al.*, 2008). The recovery of fertilizer P can be calculated in several different ways (see section 1.3.6) and lately it has been discussed whether the balance method or the difference method is most appropriate (Chien *et al.*, 2012; Syers *et al.*, 2008). The balance method, preferred by Syers *et al.* (2008), presents the PUE as the total amount of P acquired by the crop, divided by the total amount of P applied. Values lower than 100% calculated with the balance method indicate that more P is applied than is removed by the crop and thus soil P reserves are building up. A comparison between these two methods and the direct method using the dataset from Paper II shows that both produce results that differ from those obtained with the direct method, where labelled ^{32}P is used to define the actual recovery (Table 3).

Table 3. *Recovery of fertilizer P (%) calculated with the direct, difference and balanced methods. The data used in the table are average final harvest values for the two soils and the two application strategies in Paper II*

	Phosphorus supply (mg pot^{-1})			
	77	154	307	613
Direct method	12	14	17	18
Difference method	7	7	10	12
Balance method	270	138	76	45

The difference method gives lower recovery values than the direct method because it does not take into account the fact that the recovery of soil P decreases when readily available P is added. These results contradict Chien *et al.* (2012) and Hedley and McLaughlin (2005), who argue that P uptake from soil alone (soil-P) may be lower without P fertilizer than with P fertilizer. They suggested that adding P to the soil would enhance root development and thereby also increase the recovery of soil P. This might be true in cases where P is limiting plant growth, but not in cases where sufficient P is available in the soil, according to the results in Paper II.

The balance method heavily overestimates the recovery of fertilizer P and is not suitable for this purpose. However, this method is suitable for evaluating whether P application is building up, depleting or maintaining the soil P reserves over time. The method one chooses to use for calculating the PUE is therefore dependent on the purpose and set-up of the investigation.

5 Synthesis and applications

Potato is the most P-demanding of all the agricultural crops grown in Sweden and still has the highest P recommendations (Albertsson, 2012). However, the results in this thesis indicate that over recent decades, many Swedish potato fields has been fertilized with P to the extent that no further yield effect is achieved from additional P. This excessive P fertilization, resulting in reduced farm profits and environmental problems, is likely to continue until adequate knowledge is available to predict the yield response from P application. Today advisors and farmers use the P-AL value (Egnér *et al.*, 1960) and yield predictions to determine the amount of P to apply. This thesis shows that the P-AL value alone is not sufficient for predicting the yield effects from P supply, and that other factors such as buffering capacity, soil type and variety are equally, or more, important. This confirms findings in earlier studies (Mohr & Tomasiewicz, 2011; Mattsson *et al.*, 2001; Maier *et al.*, 1989).

The inventory study (Paper IV) was not designed to produce an exact description of a new recommendation model and more detailed studies are needed for that purpose. However, from the results in Paper IV it can be concluded that it is much more likely that a yield response will be achieved from P supply if the plant petiole concentration is increased by at least 1 mg P g dw^{-1}. This is very difficult to achieve if the buffering capacity is greater than 40 mmol kg^{-1}, the soil organic matter content is greater than 10%, the P-AL value is greater than 20 or the P application level is below 30 kg P ha^{-1}.

There are two scenarios where P fertilizers do not affect yield or quality: (A) When most of the P applied is adsorbed to the soil and becomes unavailable for the plant; and (B) when sufficient amounts of P are already available in the soil (Figure 9). In a scenario A soil, the recommended strategy should perhaps be to precision-place the P fertilizer and make sure that the crop is well supplied with water. The results in this thesis show that P recovery and marketable yield could be increased by up to 100% if irrigation is optimized.

This strategy may not be fully successful in soils with extremely high buffering capacity, in which case foliar application can increase yield by approximately 9% (Paper I). However, foliar P application should not be considered a general application strategy, since numerous field experiments have shown no effect (Dampney *et al.*, 2002; Allison *et al.*, 2001). This thesis shows that the foliar application should be scheduled right after irrigation or a rain event in order to be successful. Soils with extremely high buffering capacity are not common in Sweden. It has also been shown that new P fertilizer additives, such as dicarboxylic acid copolymer, can improve P recovery in potato on soils with a high buffering capacity (Hopkins, 2013). This additive is designed to minimize the concentration of potentially reactive cations in the immediate vicinity of the P fertilizer when applied to soil.

In a scenario B soil, where sufficient amounts of P are available and no yield effects are obtained from P supply (non P-responsive), no P should be added until the soil has reached the 'critical value'. When the critical value is reached, the soil P level should be kept constant by supplying P according to crop removal. With this strategy the risk of luxury consumption and leaching is minimized and the agro-economic P use efficiency is simultaneously maximized. In Sweden, non P-responsive soils are quite common (Paper IV).

Potato fields which are responsive to P fertilizer can be categorized into two categories, high and low buffering capacity soils. The same recommendation applies for the responsive soils as for the non P-responsive with high buffering capacity. The responsive fields with low buffering capacity, typically sandy soils on farms without animals, are suitable for split applications of P, especially in the case of leased land where increased soil P reserves are of no interest (Figure 9). In these cases, split application can increase the P recovery by approximately 25%.

Finally, the choice of variety may ultimately determine whether the crop is responsive to P. Efficient varieties may be able to tolerate lower available P levels in soil than less efficient varieties.

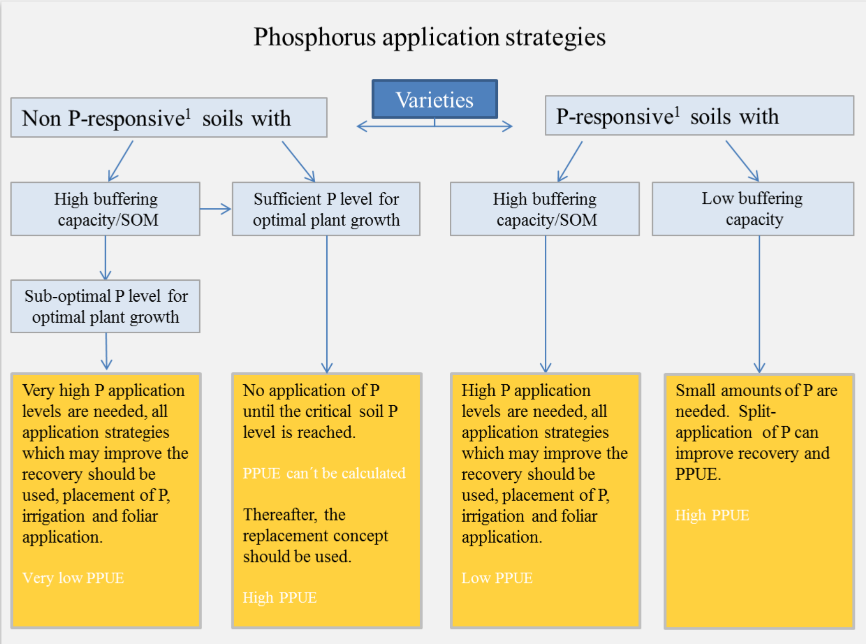

Figure 9. Decision support model for P application strategy depending on soil properties. [1]Responsive to the recommended application level.

It was shown in this thesis that subsoiling can be used to improve P recovery, PPUE and yield in potato. This strategy can be recommended regardless of soil P status. However, only soils with documented compaction and 70-90% sand in the subsoil which is relatively free from stones should be subsoiled.

6 Conclusions

Many Swedish soils contain sufficient amounts of P to support optimal growth and no longer respond to P fertilizer. Information on soil organic material, pH, buffering capacity and varietal characteristics is needed, in addition to P-AL, to predict the yield response from P supply. Phosphorus use efficiency and P recovery can be improved if P fertilizers are applied in split doses, especially in soils with low buffering capacity. Foliar application does not improve the PPUE, but can increase yield if the plant is well supplied with water. Irrigation and subsoiling also increase yield, PPUE and P acquisition.

7 Areas for future research

The present thesis increases the understanding of soil P dynamics and its influence on the responsiveness of potato to P fertilizers. However, more research is needed in order to predict yield effects adequately. More advanced models which take several soil parameters into account need to be developed. In order to predict yield effects, variety-specific data on P recovery efficiency and utilization efficiency are also needed.

The two most commonly used fertilizers used in potato cropping in Sweden today are N-P-K 11-5-18 and 8-5-19. The application rate of these two fertilizers is normally adjusted according to the crop N requirement. In many cases this leads to excessively high P levels being applied, basically because of the high P:N ratio in the mineral fertilizer. Therefore there is an urgent need for a new fertilizer product for potato which contains lower amounts of P in relation to N (and K).

Split P application demonstrated the potential to improve the recovery and PPUE of fertilizer P. Field experiments with radio isotopes are needed to confirm this finding. Such experiments should be carried out with granular fertilizer on a P-responsive soil with low buffering capacity to allow the full potential of the strategy to be evaluated.

New P fertilizer additives such as dicarboxylic acid copolymer may have the potential to improve crop P recovery on soils with high buffering capacity by minimizing the concentration of potentially reactive cations in the immediate vicinity of P fertilizer in soil. Further studies are needed to confirm the efficiency of this additive.

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Potato requires relatively large amounts of supplied phosphorus (P) to achieve adequate yields. However, P is a non-renewable resource which causes eutrophication when lost to water bodies. Consequently, efficient use of P is crucial. This thesis summarizes the current literature in the area and provides novel results from different studies regarding P supply to potato. The findings in this thesis contribute to understanding the complex dynamics of P acquisition in potato and, hopefully, to more efficient use of the non-renewable P resource.

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