Universität für Bodenkultur Wien
Department für Wald- und Bodenwissenschaften

A Comparison of Different Phosphorus Extraction Methods with the Phosphorus Uptake of Wheat

Rosemarie Wünscher

Masterarbeit
Wien, 2013

Betreuer:

Dr. Franz Zehetner

DI Hans Unterfrauner

Für meine Eltern

STATUTORY DECLARATION

I declare that I have written my thesis independently, that I have not used any other sources than the ones declared and that I have marked all material quoted literally or by content.

Vienna, September 2013 Rosemarie Wünscher

ABSTRACT

Phosphorus (P) is indispensable to life and therefore essential to plant nutrition. Rock phosphate reserves are limited demanding an optimization of the usage of P fertilizers. One step in this process is to find methods to determine the plant available P in soils accurately.

The aim of this study was to identify P extraction methods best reflecting plant available P. Fifty contrasting agricultural soils were selected from Austria and Germany. Spring wheat was grown in a greenhouse pot experiment, harvested when mature and analyzed for yield parameters and P contents. The soils were extracted with the following methods/ extractants: H_2O, $CaCl_2$, LiCl, iron oxide impregnated filter papers, Olsen, calcium acetate lactate (CAL), cation and anion exchange membranes, Mehlich 3, Bray and Kurtz II, citrate-bicarbonate-dithionite, organic P, HCl, acid ammonium oxalate, total P.

Phosphorus plant uptake was in the range of the P extracted by the weakest extraction agents. In general, the P values extracted by the 14 extraction methods significantly correlated with each other. Our results showed that H_2O and $CaCl_2$ extractable P correlated best with plant P uptake over one growing season. When grouping the soils according to pH, organic carbon content and clay content, weaker extraction methods showed analogous trends; also among the stronger extraction methods common tendencies were found.

Based on my results I conclude that a single method may not be sufficient to assess current and potential plant availability of P and to reliably predict the necessity of fertilizer applications in agriculture. Further investigations of additional soil types, of soils with very low P status, of experiments over more than one growing season and field trials could give supplementary information on the prediction accuracy of the examined methods.

ZUSAMMENFASSUNG

Phosphor (P) ist für alles Leben unabdingbar und darum auch ein essentieller Nährstoff der Pflanzen. Das Vorkommen von Rohphosphat ist begrenzt, dadurch wird die Optimierung von P Düngereinsatz immer wichtiger. Ein Schritt in diese Richtung ist Methoden zu finden, die den pflanzenverfügbaren Phosphor in Böden adäquat bestimmen.

Das Ziel dieser Arbeit war es, diejenigen Bodenphosphor-Extraktionsmethoden zu ermitteln, die die pflanzenverfügbare Fraktion am besten widerspiegeln. Dazu wurden 50 unterschiedliche Ackerböden aus Österreich und Deutschland ausgewählt. Sommerweizen wurde in einem Glashaus-Topfversuch angebaut, zur Reife geerntet und auf Ernteparameter und P-Gehalte analysiert. Die Böden wurden mit folgenden Methoden/Extrakten extrahiert: H_2O, $CaCl_2$, LiCl, Eisenoxid-Filterpapier, Olsen, Calcium Acetat- Lactat (CAL), Anionen-Kationenaustauschmembranen, Mehlich 3, Bray und Kurtz II, Citrat-Bicarbonat-Dithionit, Organischer P, HCl, Ammoniumoxalat, Gesamt-P.

Die Pflanzenaufnahme lag in der Größenordnung der schwächeren Extraktionsmethoden. Generell kann man sagen, dass die Bodenphosphorgehalte, die durch die 14 Methoden extrahiert wurden, signifikant miteinander korreliert waren. Meine Ergebnisse haben gezeigt, dass P, der durch H_2O und $CaCl_2$ extrahierbar ist, am besten mit der über eine Wachstumsperiode von Pflanzen aufgenommenen P Menge korrelierte. Bei einer Gruppierung der Böden nach pH, organischem Kohlenstoff und Tongehalt zeigten sich innerhalb der schwächeren Extraktionsmethoden ähnliche Trends. Ebenso konnten innerhalb der stärkeren Extraktionsmethoden analoge Tendenzen festgestellt werden.

Aufgrund der Ergebnisse meiner Arbeit, kam ich zu dem Schluss, dass eine einzelne Methode möglicherweise nicht ausreichend ist, um die gegenwärtige sowie die potentielle Pflanzenverfügbarkeit von P in Böden hinreichend abzuschätzen und um eine verlässliche Vorhersage über die Notwendigkeit einer Düngerapplikation in der Landwirtschaft zu treffen. Weitere Untersuchungen mit zusätzlichen Bodentypen, Böden mit sehr niedrigen P-Gehalten, Versuchen über mehr als eine Wachstumsperiode und Feldversuchen könnten ergänzende Informationen zur Schätzgenauigkeit der untersuchten Methoden liefern.

ACKNOWLEDGEMENTS

I would like to thank first and foremost my research supervisors *Dr. Franz Zehetner*, Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna and *Hans Unterfrauner*, Technisches Büro Unterfrauner, Vienna for their patient guidance, help, support and especially for the enthusiastic encouragement throughout this project. Thank you for so willingly giving your time and helping to solve every obstacle forming along the way!

My appreciation extends to *Dr. Helmut Eißner*, *Dr. Bodo Hoffmann*, *Dr. Friedhelm Herbst* (Experiment “Ewiger Roggen”), Division of Agriculture and Nutritional Sciences, Martin-Luther-Universität, Halle–Wittenberg, equally *Michael Baumecker,* Lecture and Research Station Thyrow, Humboldt-Universität zu Berlin and *Dr. Heide Spiegel,* Division of Food Security Research - Sustainable Plant Production at the Austrian Agency for Health and Food Safety (AGES), Vienna for the permission to include and for supplying very special soil samples from field experiments. Furthermore, I want to express my gratitude to all the famers who agreed to provide soil samples for my experiment.

I am very grateful for the committed support of *Dr. Albert Novotny* whose continuous advice, consultancy and periodic monitoring of the plants’ health and nutrition was very valuable for the experiment in the greenhouse.
Similarly, I would like to thank *Dr. Elisabeth Koschier*, Division of Plant Protection, University of Natural Resources and Life Sciences, Vienna for her immediate support and intervention in applying pest management.
Thank you *Dr. Gerhard Soja*, Austrian Institute of Technology (AIT), *Dr. Gernot Bodner* and *Dr. Heinrich Grausgruber*, Division of Plant Breeding, University of Natural Resources and Life Sciences for providing space and equipment to process the plant samples after harvest.
Dr. Markus Puschenreiter and *Astrid Hobel*, Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna deserve a special mention; thank you for your time and for showing me all the necessary lab procedures, in Tulln and at Türkenschanze.
I owe a heartfelt thank-you to *Dr. Robert Peticzka* of the Department of Geography and Regional Research, University of Vienna, for help with the analysis of the soils’ particle size distribution.

I also want to thank *BoWaSan/Bodenkalk e. Gen.*, Graz, *Karner Düngerproduktion GmbH*, Neulengbach, *Water and Waste* Division Agriculture and Soil Science, Leobersdorf and *Technisches Büro Unterfrauner*, Vienna.

My appreciation extends to all the friendly faces of the institute, staff members and co-workers for their help and sharing laughter during long working days. Besides, I would like to thank all my friends for moral support and assistance and always getting me back on track.

Last but not least, I wish to thank my parents and sister for inspiring me, for their ceaseless support and most importantly for providing a space to restore my energy and motivation throughout this work and the entire time of my studies.

I owe a debt of gratitude to all of you, so I am simply going to say:

Thank you very much!

Table of Contents

List of Tables

List of Figures

1 Introduction

Phosphorus (P) is a central element to life on earth. Living organisms rely on it, as it is crucially involved in most major metabolic processes, e.g. it takes on a prime role in energy transfer as adenosine triphosphate (ATP). As phospholipids, phosphorus is part of cell membranes and as part of nucleotides, phosphorus is a major component to build up DNA and RNA. Furthermore plants are dependent on phosphorus to secure energy production in photosynthesis *(SMIL, 2000, RUTTENBERG, 2009).* Due to the reasons mentioned above, the fundamental significance of phosphorus in agriculture and food production is beyond question.

In nature we can identify several phosphorus pools. The largest extent of phosphorus in the lithosphere occurs in marine and freshwater sediments (about 800-4000×10^6 Mt P), while the entire phytomass (terrestrial and marine; about 570-625 Mt P) accounts for over 90% of phosphorus stored in the totality of all living organisms (maritime and terrestrial). Phosphorus does not possess a stable gaseous compound, therefore the smallest and an only insignificant extent (0.028 Mt P) can be found in the atmosphere as dust and sea spray picked up by wind erosion *(SMIL, 2000, RUTTENBERG, 2009)*. The flows of phosphorus between these reservoirs is slow (it may take more than 1 million years). This is due to the low solubility of phosphate in water and due to the lack of an airborne reservoir. However, despite a long retention time of phosphorus in its reservoirs and relatively constant flux quantities, human activity has increased the amount of phosphorus moving within the P cycle *(LIU et. al., 2008)*.

Today, about 90% of phosphorus production is used for mineral fertilizers and fodder additives for animal husbandry, i.e. food production *(EFMA, 2000, CORDELL et al., 2009)*. The global rock phosphate mining production is continuously increasing – an annual growth of 2% is estimated by *IFA (2011)* as an average over the last six consecutive years. In 2011 it amounted to a total of 191,000 t *(JASINSKI, 2012)*. According to the US Geological Survey there are over 300 billion tons of reserves of phosphate rock worldwide, nevertheless opinions are divergent on how long these reserves will last. In this context the term 'peak phosphorus' was introduced by *CORDELL et al. (2009)* indicating the time when the maximum rate of rock phosphate mining is approached. Beyond this point minable ores are expected to be of minor quality, harder accessible and therefore less economical to degrade, yet the demand will be on the rise. The authors concluded a peak will appear around the year 2033. How long global phosphate rock reserves will last is being discussed controversially by multiple authors. Based on differing reserve assumptions (reserve and reserve base; cf. USGS 2006) and dissimilar scenarios for the growth of earth's population and accordingly growing fertilizer demand, estimates for the depletion of phosphate rock reserves may vary between 50 years to 400 years (even 1000 years; cf. *EFMA*, *2000*). However, a majority comes to the conclusion that the depletion will occur within the next 100 years *(CORDELL et al., 2009, CORDELL and WHITE, 2011, COHEN et al. 2011, SMIT, 2011)*. Some factors considered relevant for the accelerating depletion of the reserves are the increasing world population causing rising food demand, the changing of diets (of low income economies) towards a phosphorus-intensive, meat-based diet, and the increasing production of biofuels, all of which increases the demand for fertilizers. While on the contrary increasing costs for mining (increasing oil costs), increasing costs for fertilizers and increasing consciousness of over-fertilization and of eutrophication problems may diminish demand and therefore delay a production depletion *(CORDELL et al., 2009, CORDELL and WHITE, 2011)*.

Recently, *RECHBERGER et al. (2013)* have assessed the situation and phosphorus flows in Austria and presented losses, the potential to recycle and possible scenarios for regaining P from sewage sludge and meat and bone meal. In Germany, *RÖMER (2006)* assessed recycling products regarding P availability for plants and P uptake to predict their usability for fertilization.

With regard to phosphorus fertilization two major issues concerning environmental and economic problems are of interest: on the one hand contamination of fertilizers with heavy metals and radionuclides and on the other hand eutrophication.

The quality of rock phosphate that is extracted is highly variable; the concentration of toxic elements depends on its origin (parent material - igneous rock or sedimentary ores), the region of mining and the manufacturing process of the fertilizers *(MORTVEDT and BEATON, 1995)*. In fact, all phosphorus reserves are contaminated with heavy metals or radionuclides. In this context uranium and cadmium are of particular significance *(COHEN et al. 2011)*. The degree of contamination differs considerably; higher concentrations are found in particular in phosphate rock from sedimentary origin, which accounts for about 80% of phosphate rock processed *(COHEN et al. 2011 citing STEWART, 2005)*. Notable is, that a contamination of cadmium and uranium simultaneously, will multiply their toxicity. Accumulation of these toxic substances in agricultural soils and especially their runoff to groundwater can pose a potential danger to human health *(SCHNUG, 2012)*.

Eutrophication plays a major role in terms of lake and fresh water pollution. The runoff of phosphorus from (agricultural) topsoil layers provides an oversupply of phosphorus in surface water, which leads to excessive plant growth and causes a major disturbance of the biologically balanced dynamics in the waters. As a consequence of abnormal algal growth – and the resultant high biological activity of decomposer organisms – the amount of oxygen and light in the water severely decreases, leading to fundamental change of fish species compositions and often resulting in mass mortality of fish and other oxygen dependent organisms *(LIU et al., 2008, SMIL, 2000)*.

In soils, phosphorus is mainly drawn from weathering processes of the mineral apatite *(SCHLESINGER, 1997)*. Soil phosphate can be classified into four pools: dissolved in soil water, sorbed to surfaces of clay minerals or Fe and Al oxides, primary phosphate minerals and in organic substances and living organisms. The average total phosphorus in soils ranges from 200 mg kg^{-1} (in older, highly weathered soils) to 800 mg kg^{-1} (in younger soils) *(ZEHETNER et al., 2008)*, the average amount of organic P ranges between 30% and 65% of the total P *(CONDRON and TIESSEN, 2005)*. The average concentration of phosphorus in plant tissues is variable; depending on the time of sampling, phosphorus in wheat shoots may range between 2.5 to 4.9 g kg^{-1} *(FANGERIA, 2009)* and phosphorus in plant seeds can amount up to 4.0 g kg^{-1} *(TIESSEN, 2008)*. A shortage of P – depending on crops – causes a decrease of tillering and branching, reduced plant growth and also limited root growth. Phosphorus further improves the shoot strength and crop quality (necessary for the development of seeds, fruit and leafs) and is a component necessary in the process of N-fixation by legumes. Typically, plants which are P deficient show dark green color of leafs, as the reduced growth but similar amount of chlorophyll increases its proportion per leaf area; on older leafs a purple or reddish color may be noticed *(FANGERIA, 2009)*. Plants mainly take up phosphorus in forms of inorganic ions, either $H_2PO_4^-$ (in acidic soils) or HPO_4^{2-} (in alkaline soils) *(BLUME et al., 2010)*. The availability of phosphorus to plants is dependent on the pH of the soil solution; when the pH is low (in the acidic range) phosphate is mainly found sorbed on Al and Fe oxides while a pH close to neutral promotes a fixation as Ca phosphate *(LIU et al., 2008)*.

HOLFORD (1997) and *FROSSARD et al. (2004)* have classified phosphorus availability using the concept of intensity factor, quantity factor and capacity factor. The intensity factor gives the concentration of phosphate that is readily solved in the soil solution. The quantity factor describes the total amount of phosphorus that is in the soil and may be solved and taken up by the plant eventually. The capacity factor expresses the capacity of soils to stabilize the magnitude of the intensity factor even when the quantity factor changes. The relation of intensity and quantity factor may provide information on the ability of the soil to resupply nutrients for plant uptake.

In agriculture a balanced availability of nutrients is not only the basis to achieve satisfying yields with excellent quality but simply to produce healthy plants. Nutrient availability affects the crop and farm management as it influences the amount of fertilizers, pesticides and herbicides that have to be applied. Due to the scarcity of phosphorus resources an efficient use of phosphorus is crucial; optimizing plant nutrition and fertilization is one step to guarantee global food production. To secure plant availability while reducing environmental risks an accurate forecast of the plant available nutrient status in agricultural soils is indispensable.

Today, there is a multitude of soil extraction methods available, and even in routine soil testing diverse extraction methods are used. While the calcium acetate lactate (CAL) extraction is used in routine soil testing in Austria and Germany, Mehlich 3 is used in the Czech Republic and in major parts of Canada and the United States of America. On the contrary, Brazil is using a more recently established extraction method on the basis of anion exchange membranes.

Based on the fact that different P extraction methods are used all over the world, which complicates the comparability of results, the aims and objectives of this work were:

I) to compare several extraction methods in contrasting soils, and
II) to identify extraction methods that best represent phosphorus uptake by plants through relation to plant phosphorus uptake (after one growing season)

2 Materials and Methods

2.1 Description of Investigated Soils

Soil samples were taken in the period from mid-March to mid-April 2011 in a depth of 0-30 cm from agricultural soils in Austria and Germany. The soils were chosen to be dissimilar in soil properties to cover an interesting spectrum of soil types and a wide range of phosphorus availability. In advance, the samples were not specifically fertilized with P to contain different levels of phosphorus but were solely treated according to common farm management. Hence, the famers applied different fertilizers depending on e.g. the crop rotation and crop types. To guarantee a broad range of phosphorus levels the 50 soils were selected from a total of 83 samples according to the amount of phosphorus extracted by calcium acetate lactate (CAL) and anion exchange membranes (CAEM).

Most soils were just represented once in the experiment; however, some of the samples belonged to long-term experiments. Then, similar soils with different treatment of fertilization were compared, having otherwise the same management. All other soils were managed with diverse tillage, fertilization and crop sequences before the experiment took place.

2.2 Soil Analysis

In this chapter a basic overview on selected physiochemical properties and a detailed description of the applied extraction methods are given.

2.2.1 Determined Basic Soil Properties

The soil data gathered for this work amounts to an extensive analysis of physicochemical parameters. Only selected soil parameters could be elaborated in this thesis, as a detailed discussion of all would go beyond the scope of this work.

A thorough analysis of the soil parameters is important as they influence the performance of the various extraction methods. For example, some of the extraction methods have a certain pH range at which they extract properly.

The pH was determined in a H_2O saturation extract and also in 0.5 M KCl with a soil-to-solution ratio of 1:2.5 (volume ratio) as described in *OENORM S 2122-1 (2004)*, the electrical conductivity (EC) was measured in the water saturation extract. Total carbon contents were measured by dry combustion as described in *OENORM L 1080 (1999)* and carbonate contents ($CaCO_3$) were determined by the Scheibler method as described in *OENORM L 1084 (2006)*. Organic carbon (OC) was calculated as the difference of total and carbonate carbon. In order to calculate the ratios of C/N, C/P and N/P on a molar basis, additionally total soil N was determined by dry combustion according to *OENORM L 1080 (1999)* and total P contents as described in chapter *XIV Total P*. Furthermore, the KH value was calculated as described in *OENORM S 2122-1 (2004)*. This value represents the amount of water contained in the soil at saturation, which is individual for each soil.

The potential cation exchange capacity (CEC_{pot}) was determined by extraction with a 0.4 M LiCl solution buffered at pH 8.1 with triethanolamine. To this end, 50 mL of the solution was shaken with 40 g of water-saturated soil for 2 h, centrifuged and the supernatant was transferred into a flask; the soil sample was then mixed with another 50mL, shaken, centrifuged and the supernatant added to the flask. The solution was filtered with a membrane filter, exchangeable cations were measured and the CEC_{pot} calculated in $cmol_c\ kg^{-1}$ DM (dry matter) as described in *OENORM S 2122-1 (2004)*. The base saturation and the respective cations were calculated in percent of CEC_{pot}. Oxidic iron and manganese was extracted with dithionite-citrate-bicarbonate (Fe_d, Mn_d) *(MEHRA and JACKSON, 1960)* and also by acid ammonium oxalate (Fe_o, Mn_o; extracting only the poorly crystalline forms) according to *OENORM L 1201* (2007); the extracted Fe and Mn was measured by atomic absorption spectroscopy (AAS). The molar ratios of Fe_o/Fe_d and P_o/Fe_o were calculated based on the measurements of Fe and P in the oxalate and dithionite extractions.

The soil particle size distribution was determined by use of wet-sieving and sedimentation in a sedigraph after adding H_2O_2 to remove organic matter and dispersing with sodium metaphosphate, modified according to *OENORM L 1061-1 (2002)* and *OENORM L 1061-2 (2002).*

2.2.2 Applied Soil P Extraction Methods

In advance all soil samples were dried at 50°C and sieved to smaller than 2 mm. For every chemical analysis blank and reference samples were carried along and treated similarly.

The same extracting solution was used as a background solution for the blanks, standards and for the extraction of the samples. All methods were undertaken at room temperature. If filtration was necessary the first few mL were discarded, the quantity depending on the total amount of solution output. Munktell folded paper filters (grade 14/N) were used for the filtration of all extractions.

A brief summary of the 14 applied methods is given in Table 1. The table provides an overview of the composition of the extracting solution, the soil-to-solution ratio, the extraction time and the method of measurement that was applied.

Table 1: Overview of the studied soil P extraction methods

Method	Extracting solution	Soil-to-solution ratio	Shaking time	Method of measurement
H_2O	distilled H_2O	1:0.3 to 1:1.2	(ca.12 h)	ICP; Photometer
$CaCl_2$	0.01 M $CaCl_2$	1:10	2 h	ICP; Photometer
LiCl	0.4 M LiCl	1:1.8 to 1:4.0	(2 × 2 h)	ICP
[a] **Fe-oxide P_i**	(0.01 M $CaCl_2$)	1:40	16 h	Photometer
Olsen	0.5 M $NaHCO_3$; pH 8.5	1:20	30 min	ICP; Photometer
[b] **CAL**	0.3 M CH_3COOH, 0.05 M $C_6H_{10}CaO_6 \times 5 H_2O$, 0.05 M $(CH_3COO)_2 \times H_2O$	1:20	2 h	ICP; Photometer
[c] **CAEM**	(distilled H_2O)	1:40	16 h	Photometer
Mehlich 3	0.2 M CH_3COOH, 0.25 M NH_4NO_3, 0.015 M NH_4F, 0.013 M HNO_3, 0.001 EDTA	1:10	5 min	Photometer
Bray II	0.03 M NH_4F, 0.1 M HCl	1:7	40 sec	Photometer
Dithionite	0.2 M $NaHCO_3$, 0.12 M NaS_2O_4, 0.24 M $C_6H_5Na_3O_7 \times 2 H_2O$	1:50	16 h	ICP
Organic P	[d] (1 M HCl)	1:100	16 h	Photometer
HCl	0.5 M HCl	1:10	2 h	ICP
Oxalate	0.08 M $(COOH)_2 \times 2 H_2O$, 0.11 M $(COONH_4)_2 \times H_2O$; pH 3.0	1:50	4 h	ICP
Total P	1 M HCl (after calcination)	1:100	16 h	Photometer

[a] Fe-oxide P_i = iron oxide impregnated filter paper

[b] CAL = calcium acetate lactate

[c] CAEM = anion exchange membrane

[d] Organic P was determined as the difference of P extracted with 1M HCl before and after calcination

I. Water Extraction (H_2O)

In order to produce the water extraction, the steps described in *OENORM S 2122-1 (2004)* were followed. This method is based on the preparation of a water saturation extraction that is described in *OENORM L 1092 (2005)*. Accordingly, the amount of water the sample is able to take up was added until the liquid limit was reached (the quantity is specific for each soil). About 300 g of field-moist soil sample was sieved to <5 mm and moisturized while stirring until saturation (i.e. when tilting the flask, the sample starts to flow slightly) was obtained. The solution was allowed to stand for one hour, and then the saturation level was checked. If after that hour a water film had formed on top, more soil needed to be added, if the soil suspension had stiffened after that time, more water was necessary. In case of adjustment, the suspension had to be rechecked after another hour. When the state of saturation was attained the supplied amount of water was weighed, the extraction was covered and allowed to equilibrate over night at room temperature. The next day it was centrifuged with 2500 *g* for 15 min and subsequently filtered by membrane filters. This extraction method was measured by ICP-OES and by photometer.

The water extraction determines the phosphorus in the soil solution, thus dissolved or readily soluble forms of phosphorus.

II. $CaCl_2$

The $CaCl_2$ method was prepared as described in *HOUBA et al. (2000)* using 5 g of soil in 50 mL of extracting solution (0.01 M $CaCl_2$). The solution was shaken for 2 h and then filtered. The samples were measured by ICP-OES and colorimetrically by photometer.

This method is based on the principle of a (dilute) salt solution inducing an ion exchange but nevertheless relies mostly on the dissolution of phosphorus in the extraction solution *(VAN RAIJ, 1998)*.

III. LiCl

The LiCl extraction method was carried out according to instructions in *OENORM S 2122-1 (2004)*. In advance the field-moist soil samples were sieved to <5 mm and then a water saturation extraction was prepared as described for H_2O extraction and in *OENORM L 1092 (2005)*. Of this soil-water mixture 40 g were shaken for 2 h with 50 mL of extraction solution (0.4 M LiCl). Thereafter it was centrifuged and the liquid phase transferred to a separate flask, while the solid phase was shaken for a second time with additional 50 mL of 0.4 M LiCl for an extra 2 h. After centrifugation the supernatant was also transferred to the flask containing the first subset. At last this suspension had to be filtered through a membrane filter. The LiCl extractions were measured by ICP-OES.

This method is based on a pH-neutral salt solution suitable for a vast range of soil properties. Due to the characteristics of Li (small ion-diameter, thick hydration shell, weak electrostatic charge), LiCl extracts only easily exchangeable cations and soluble phosphorus forms *(HUSZ, 2001)*.

IV. Iron Oxide Impregnated Filter Paper (Fe-oxide P_i)

This method was performed on the basis of the protocol by *CHARDON (2000)*. The preparation of the filter papers: As a first step a solution of 0.62 M $FeCl_3$ was produced in dilute HCl. Every filter paper was treated with this solution for at least 5 min; afterwards they were allowed to dry for an hour. When the papers were dry, a 2.7 M NH_4OH solution was prepared and every filter paper was pulled through the solution rather quickly and constantly with (plastic) tweezers. Thereby amorphous iron-oxides formed on the filter paper; immediately following the filter papers had to be washed with distilled water to assure that any loose iron-oxide particles were removed. Next, the impregnation of the filter papers were dried and cut into quarter slices. The prepared filter papers were folded thoroughly and put into nets made of polyethylene and tied with a fishing line (likewise made of polyethylene). This protection net was put around the filter papers to keep the bigger soil particles from scratching off the iron oxides while shaking. Polyethylene was selected as material of choice because it is inert and should not affect the chemical process of dissolution and adsorption of phosphorus to the oxides on the filter paper. In Figure 1 the paper slices, folding and the nets are illustrated.

For the extraction 1 g of soil along with 1 bag of filter paper were mixed with 40 mL of 0.01 M $CaCl_2$ solution, and then this soil suspension was shaken for 16 h. After the shaking filter papers were taken out and washed properly to assure no soil particles being stuck on the filter paper. After that the filter papers were put in 40 mL of 0.1 M H_2SO_4 and shaken for 1 h in order to elute the P. This solution was then measured by photometer.

This method is based on an infinite P sink approach. The iron oxide filter papers serve as a P sink imitating the plant root. Through sorption of P from the solution to the filter paper a further desorption/ re-supply from the soil is induced *(MYERS, et al. 2005)*.

Figure 1: Preparation of the iron oxide impregnated filter papers: cut, folded and put into protection nets

V. Olsen

This extraction method was introduced by *OLSEN et al. (1954)*, our extraction was carried out according to *SIMS (2000)* except for a minor modification; we used 2 g (instead of 1 g) of soil sample that was mixed with 40 mL (instead of 20 mL) of extracting solution, nonetheless maintaining the soil-to-solution ratio of 1:20. The extracting solution was prepared of 0.5 M $NaHCO_3$ and adjusted to a pH of 8.5. The samples were shaken for 30 min at room temperature, filtered, and measured by ICP-OES and photometer.

In general, the Olsen method is preferably used for calcareous soils (>2% $CaCO_3$) but studies have shown that also values for non-calcareous give reasonable results *(FRANK, et al., 1998).* The Olsen extraction reduces the Ca^{2+} in the solution, as $CaCO_3$ precipitates and therefore causes a better Ca-phosphate dissolution. The phosphate adsorbed on the Ca-carbonate and Fe-oxide surfaces is extracted by this method *(SIMS, 2000, SCHOENAU and O'HALLORAN, 2007).*

VI. Calcium Acetate Lactate (CAL)

The calcium acetate lactate method will be further referred to as CAL. The CAL procedure is used as the standard method in routine soil testing in Austria and Germany. This extracting method was carried out according to *OENORM L 1087 (2006)*. Although in *OENORM L 1087 (2006)* 5 g of soil is mixed with 100 mL extracting solution we used 2.5 g of soil in 50 mL extraction solution preserving the soil-to-solution ratio of 1:20. The extracting solution was prepared of 0.05 M calcium lactate ($C_6H_{10}CaO_6$ x 5 H_2O), 0.05 M calcium acetate ($(CH_3COO)_2Ca$ x H_2O), 0.3 M acetic acid (CH_3COOH). The solution was shaken end-over-end for 2 h. Subsequently, the samples were filtered and then they were measured by ICP-OES and by photometer.

According to *SCHÜLLER (1969)* who introduced this method, the CAL method extracts only the readily soluble, exchangeable phosphates and easily dissolved Ca-phosphates from fertilizers, neglecting the P of apatitic phosphates. However, is not well suited for soils with a pH below 6 as in acidic soils the apatitic phosphate might not be determined since it is re-adsorbed by Al- and Fe-phosphates.

VII. Cation and Anion Exchange Membranes (CAEM)

The anion exchange membrane method is used in routine soil testing in Brazil. The method used in this study was performed similarly to protocols described by *NUERNBERG et al. (1998)*, *BISSANI et al. (2002) and FERNANDES and COUTINHO (1997)*. The cation and anion exchange membranes were obtained from Membranes International Inc. and cut to 1 cm broad and 7.5 cm long strips. The average weight of the anion strips was 0.377 g per strip with a total exchange capacity of 1.3±0.1 meq g^{-1} (the average weight of one cation strip was 0.443 g with a total exchange capacity of 1.6±0.1 meq g^{-1}). After cutting they were put into a 0.5 M sodium bicarbonate solution ($NaHCO_3$) for 62 h. The solution was renewed and after another 19 h the strips were rinsed five times with distilled water.

For the extraction procedure 1 g of soil was put into a tube of 50 mL and combined with one strip anion exchange membrane and one strip cation exchange membrane and 40 mL of distilled water. The samples were shaken end-over-end for 16 h. Afterwards the membranes were washed thoroughly until no soil particles were left. The anion exchange membranes were put into 40 mL of 0.5 M HCl solution and shaken for 90 min. After this time all the adsorbed ions should have desorbed from the membrane and should be dissolved in the solution. Subsequently the membranes were taken out of the solution and rinsed with water and as the membranes are reusable they were put into 0.5 M sodium bicarbonate for regeneration as shown in Figure 2. The amount of phosphorus in the HCl solution was detected by a photometer.

Similarly to the procedure of the iron oxide impregnated filter paper, this method is based on a sink concept. The exchange membranes simulate the root system in the soil, keeping the P solution concentration low and thus inducing re-supply from the soil solid phase *(VAN RAIJ,1998, KUO, 1996)*.

Figure 2: Anion and cation exchange membranes in 0.5 M sodium bicarbonate for regeneration

VIII. Mehlich 3

The Mehlich 3 extraction is employed as a standard method for phosphorus extraction in the Czech Republic and is also widely used in routine soil testing in the USA and Canada. This method is considered to be suitable for a vast range of soils varying in their physicochemical properties *(SIMS, 2000, FRANK et al., 1998)*.

The method was introduced by *MEHLICH (1978)* for the extraction of the soil samples the protocol described by *SIMS (2000)* was used. The extracting solution was prepared of 0.2 M acetic acid (CH_3COOH), 0.25 M ammonium nitrate (NH_4NO_3), 0.015 M ammonium fluoride (NH_4F), 0.013 M HNO_3 and 0.001 M ethylenediaminetetraacetic acid (abbreviated as EDTA) ($(HOOCCH_2)_2$ NCH_2CH_2N $(CH_2COOH)_2$). According to the soil-to-solution ratio of 1:10, 2 g of soil were mixed with 20 mL of extracting solution and shaken for 5 min at room temperature. After filtration the samples were measured photometrically.

As this extraction is a multi-nutrient extraction method – determining P, K, Ca, Mg, Na, Cu, Zn, Mn, B, Al, Fe – many mechanisms are combined to enable the extraction of this amplitude of nutrients. For this method the approach to extract P is an acetic acid solution, promoting the dissolution of Ca-phosphates with an addition of ligand exchange by ammonium fluoride releasing the phosphate by building a new complex with F^-. The elements K, Ca, Mg and Na are extracted by ammonium nitrate and nitric acid, while Cu Zn, Mn and Fe are dissolved and complexed by ammonium nitrate and EDTA, which hereby functions as a chelating agent *(SIMS, 2000, ZIADI and SEN TRAN, 2007, KUO, 1996)*.

IX. Bray and Kurtz II (Bray II)

This method was performed following the procedure of *BRAY and KURTZ (1945)*. 1 g of soil was weighed into a bottle and mixed with 7 mL of extraction solution. Accordingly the solution was prepared in a soil-to-solution ratio of 1:7 with an extracting solution of 0.03 M NH_4F and 0.1 M HCl. The samples were then shaken for 40 seconds. Then the solution was filtered and measured by photometer.

The Bray II extraction is considered to extract Al bound phosphates as the F^- is exchanged and forms new complexes with Al, simultaneously prohibiting a fixation by soil colloids *(KUO, 1996),* while the dilute HCl dissolves the Ca-phosphates.

X. Dithionite

The dithionite extraction was introduced by *MEHRA and JACKSON (1960)* and is not considered a conventional phosphorus extraction method. Procedure was executed following the instructions of *HOLMGREN (1967)*.

In order to prepare the extracting solution 0.2 M $NaHCO_3$, and 0.24 M sodium citrate ($C_6H_5Na_3O_7$ × 2 H_2O) were mixed. Then 2 g of soil were put into 100 mL extracting solution and 2 g of solid Na-dithionite (0.12 M NaS_2O_4) was added. The solution was shaken for 16 h and then filtered (the first 10 mL were discarded). The samples were measured with ICP-OES.

The Na-dithionite functions as a reduction agent, the citrate as a chelating agent. With this method the total secondary free Fe with the exception of magnetite *(RAISWELL et al., 1994)* was solubilized *(MEHRA and JACKSON, 1960)*.

XI. Organic P

Organic P is a calculated value. It was determined from total P and inorganic P as described below.

In order to determine the inorganic phosphorus in the soils, the first step was to grind and homogenize the sample thoroughly. Subsequently, a homogeneous soil sample of 2 g was used for the extraction procedure, which was carried out (with minor modifications) according to *PARDO et al. (2003).* The soil-to-solution ratio was 1:100; hence the 2 g were mixed with 200 mL of 1 M HCl. The extraction time was set to 16 h. The analytical determination was carried out by photometrical measurement. Organic P was then calculated by subtracting the values for inorganic P from the values gained by the total P method (s. below).

XII. HCl

The HCl extraction is also not a conventional phosphorus extraction method. To carry out the extraction a 0.5 M HCl solution was prepared. The soil-to-solution ratio was 1:10 and end-over-end shaking time was 2 h. Afterwards the solution was centrifuged for 15 min at 2500 *g*. The supernatant was transferred to a separate flask and filtered through a membrane filter (0.20 µm). The final solution was then measured by ICP-OES.

The method is based on the dissolution of inorganic phosphorus forms. Phosphorus originating from apatite is dissolved as well as Fe oxide-sorbed phosphorus (at least partly) *(Kuo, 1996)*.

XIII. Oxalate

The oxalate extraction method is not a conventional phosphorus extraction method, but derives from soil iron analysis methods. To produce this extraction the protocol of *Oenorm L 1201 (2007)* was followed. As the solution is light-sensitive, the very first step was to ensure that all flasks (both the flasks for extracting procedure and also the ones after filtration for storage until measurement) were impermeable for light. The extraction solution consisted of 0.8 oxalic acid ($(COOH)_2 \times 2\ H_2O$) and 0.11 M ammonium oxalate ($(COONH_4)_2 \times H_2O$) and the pH was set to 3.0. Then 1 g of soil was mixed with 50 mL of extracting solution. The solution was shaken for 4 h and then filtered in the dark. The oxalate solutions were measured by ICP-OES.

By this method poorly crystalline Fe was extracted, which approximates the amount of ferrihydrite and Fe associated with organic matter *(Campbell and Schwertmann, 1984)*.

XIV. Total P

To determine the total phosphorus, 2 g of homogeneous soil sample was ignited in a muffle furnace and held at 550°C for 1 h. The residue was transferred to an extraction bottle and extracted with 1 M HCl at a soil-to-solution ratio of 1:100 for 16 h. The analytical determination was carried out photometrically.

The organic phosphorus fraction is turned to inorganic forms of phosphorus by calcination. Thereafter, the total amount of phosphorus in soil (inorganic and former organic) is extracted quantitatively by HCl (modified on the basis of *Pardo et al., 2003).*

2.3 The Greenhouse Pot Experiment

The pot experiment was carried out in a greenhouse with automatic climate control through ventilation but no air conditioning for cooling. As a preliminary measure the tap water in the greenhouse was tested regarding traces of phosphorus, to assure no fertilization would take place by irrigation. The water used for irrigation was put in advance into a barrel in the greenhouse to allow it to reach “room-temperature”, avoiding a temperature shock of the plant roots.

2.3.1 Set-up of the Pots

The very first step was to homogenize the soil samples. The entire amount of one sample was mixed well in a container. Any big stones and other unwanted objects (wood, plastic, and so on) were removed and large aggregates were crushed. Figure 3 shows a schematic illustration of the layers of each pot.

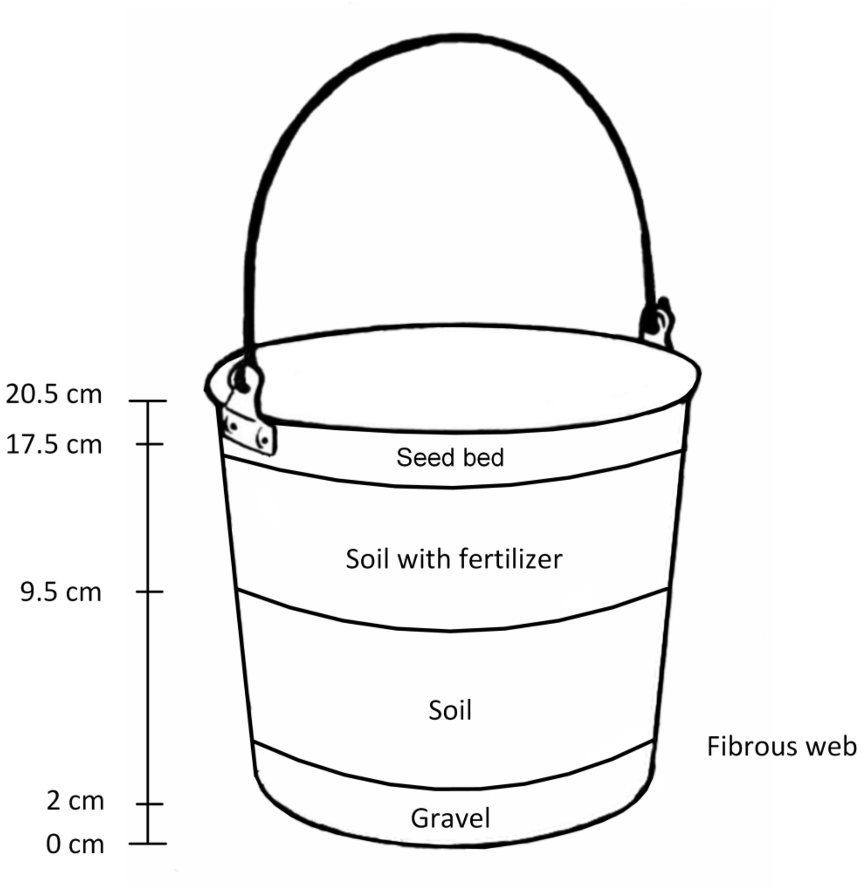

Figure 3: Schematic illustration of the set-up of a pot

The pots were prepared from 12 L buckets. 13 holes – each with a diameter of 10 mm – were drilled on the bottom of each bucket to avoid stagnant water. A 2 cm thick layer of gravel was placed as drainage layer at the bottom. The quartz gravel was washed to remove any dust and to make sure that only pure gravel was left. In order to keep the soil from washing out and to provide a barrier between the soil and gravel layer, a fibrous web was placed in between. One layer of sample prepared beforehand was filled into the bucket and re-compacted a bit then another layer of soil was put thereupon. This layer was mixed well with 0.8 g KCl fertilizer (each pot) and also this layer was again compacted a bit. The top 3 cm were sieved in order to offer an ideal seed bed later on. The total filled soil volume was 10.88 L. The sequence of the working steps is shown in Figure 4 below.

Figure 4: Pictured illustration of the working steps necessary to prepare the pots

2.3.2 The Experimental Procedure

The experiment started on May 2nd, 2011 with sowing the spring wheat and ended on July 28th, 2011 with harvesting the plant material, amounting to a total of 88 days test duration.

Pots prepared as described in chapter 2.3.1 were set up for sowing by first watering them. A master plate was used to standardize the pattern and the distance of the seeds. 19 grains were sown in each of the buckets in a depth of about 2-3 cm and afterwards watered carefully. In Figure 5 this process is illustrated in detail.

Figure 5: Pictured illustration of the sowing process

During the growing phase the pots were watered according to necessity depending on e.g. the weather and the growing stage of the plants. The soil water content was monitored by soil moisture sensors (four Decagon ECH2O Dielectric Aquameter sensors and one Decagon 5TE) in five representative pots highly varying in soil properties (to have references for all 50 pots included in the experiment). Soil water was kept near field capacity. On average the pots were irrigated every 1.8 days with an average of about 340 mL each time and pot. The average soil temperature measured by the Decagon 5TE sensor amounted to 24.9°C with a normal day to night fluctuation and a minimum at 18.8°C and a maximum of 36.6°C.

A common fertilization strategy was applied for the spring wheat plants. Details on measures and the time of application are given in Table 2 below. In total, the applied fertilizers added to 221.69 kg N ha^{-1} and 79.03 kg K ha^{-1}.

Table 2: Application of fertilizer over the duration of the experiment

Date	Fertilizer application per m²
2. May	15.07 g KCl
9. May	48.97 g [a] NAC 27 granulate
19. May	11.09 g Ammonium nitrate
14. June	22.60 g [b] Urea fertilization
22. June	1.00 g [b] Urea leaf fertilization

[a] NAC 27 = NAC with 13.5% N derived from nitrate N and 13.5% N derived from ammonium N
[b] Urea = 46% N

The plants were constantly monitored regarding unusual changes in vegetation and diseases. When a moderate infestation of thrips occurred, measures were taken as described in detail in Table 3 below. A biologic method of pest control was implemented when spider mites infested the spring wheat plants. Only measures that would not interfere with the experimental outcome were considered. Sulphuric treatment and predatory mites were applied; in addition a high humidity was maintained to keep the infestation at a minimum. The feeding damage by the thrips infestation is shown in Figure 6 below.

Figure 6: Feeding damage caused by moderate thrips infestation

Table 3: Detailed description of pest management measures and of the time of application

Date	Pest management application per m²
20. May	Fungicide: application of 14.05 mL H_2O + 0.04 mL acetate + 0.14 mL sulfate + 0.02 mL Gladio (active agent)
21. June	Insecticide: 100 mL application of 'Campo Schädlingsfrei plus' (active agent 4.59 g L^{-1} pyrethrine)
22. June	Fungicide: application of 20 mL H_2O + 0.05 mL acetate + 0.20 mL sulfate + 0.03 mL Gladio (active agent)
1. July	Insecticide: application of 20 mL H_2O + 0.08 mL adhesive + 0.40 g wettable sulphur
4. July	0.5 L insecticidal soap (potassium salts of fatty acids 10.2 g L^{-1}) 265 predatory mites (Phytoseiulus persimilis)
7. July	26 predatory mites (Phytoseiulus persimilis) 100 predatory mites (Phytoseiulus amblyseius swirskii)

The progress of the experiment is illustrated graphically from the beginning of germination to the ripening of the ears in Figure 7 below.

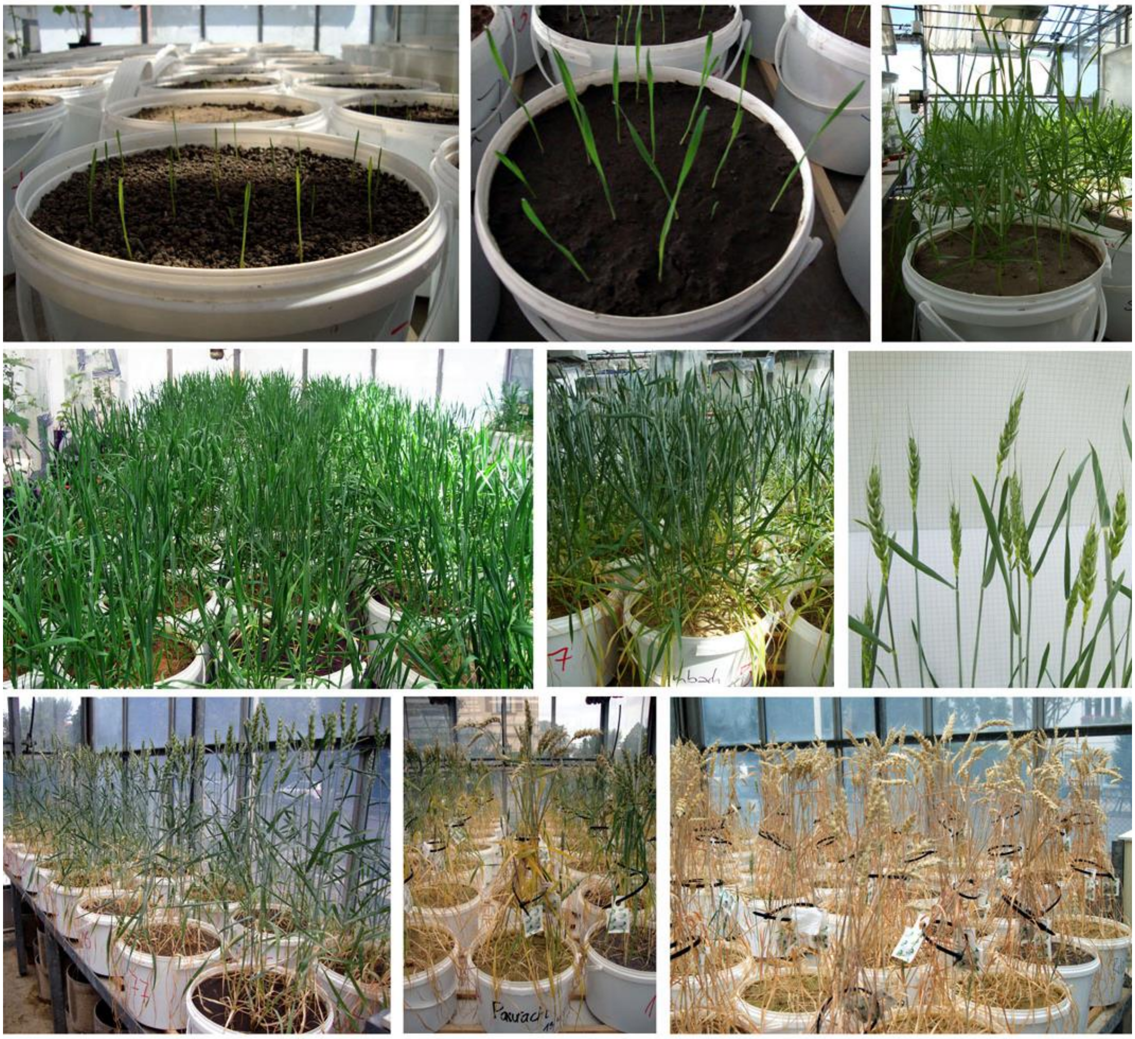

Figure 7: Experimental progress: development of the plants

Before harvesting, the plants were not watered for a longer period of time in order to guarantee ripening. All plants were harvested at once, whereupon parameters were measured as described in chapter 2.4 below. Also straw was separated from the ears on-site. For analysis all the plant material was dried and milled. The grain was threshed, counted and weighed afterwards.

2.4 Plant Analysis

Most of the plant parameters were determined at harvest. The tillering was determined by the number of stalks (green and ripened). Additionally the number of stalks with ripe ears and without ripe ears were counted. The thousand seed weight, number of ears and number of grains per ear were recorded. The weight of the straw and the weight of the grain per m^2 were determined.

The straw was dried at 50°C for three days, after that it was weighed immediately. The next step was to grind each sample to improve the performance of digestion. The grain yield was also dried and then weight and calculated back to the 14% water content that is conventionally used for the thousand seed weight. The grain was dried as it was important to have dried material for the digestion. The grain samples were also ground to assure complete digestion later on.

2.4.1 Digestion Method

In order to analyze the plant samples the straw was dried separately from the grain. Next, each sample was ground with a hand mill to facilitate and assure a complete digestion of the samples later on. A plant material sample of 200 mg was digested with 5 mL HNO_3 and 1 mL of H_2O_2. The tubes were left in a fuming hood to react overnight. Hereby it is important to put the cooler tubes immediately onto the tubes as the reaction produces a lot of foam and the reacting material might rise within the tubes and even leak out. The next morning the digestion program was run according to program settings given in Table 4.

Table 4: Program settings for the plant digestion

Temperature	Lapse Time
[°C]	[min]
65	25
110	10
155	190

The solutions were diluted with approximately 30 mL of distilled water and vortexed. The exact weight of each sample was noted, in order to be able to calculate back on the exact dilution by the water. At last, the solutions were filter by paper filters and then measured by photometer. Note that it was necessary to acid wash all the flasks and tubes that were used for the digestion, as to avoid any contamination by residuals of previous runs. Figure 8 below displays the digestion tubes while running the program.

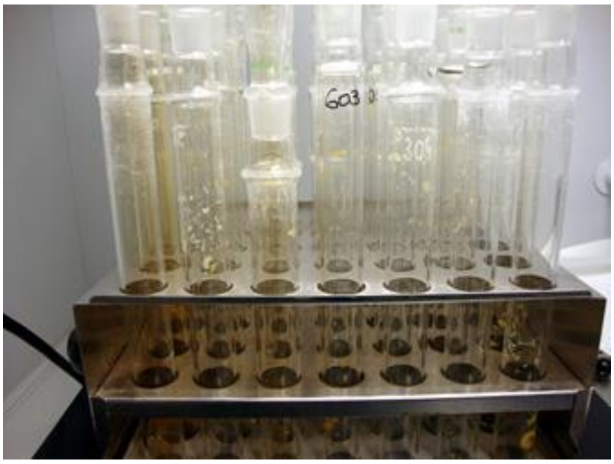

Figure 8: The tubes in the digester with plant material and HNO_3 and H_2O_2 during the run of the digestion program

2.5 Instrumental Phosphorus Analysis

Two different instruments of measurement were used to determine the phosphorus in the extraction solutions. On the one hand ICP-OES and on the other hand the photometer. When using the photometer there were two further methods to color the solutions as described in chapter 2.5.2.

2.5.1 Inductively Coupled Plasma - Optical Emission Spectrometry (ICP - OES)

The ICP-OES measures the total amount of P in the solution, whereas the colorimetric method determines only the ortho-phosphate amount in the solution *(OENORM L 1087, 2006).* One advantage of this measuring method is that ICP-OES is able to detect more than one nutrient at once, while the colorimetric measurement is only capable to determine phosphate *(PIERZYNSKI et al., 2009)*. Also, the ICP-OES can measure P in solutions where the matrix disturbs the color formation of the photometric method.

2.5.2 Photometer

The photometer is a device to detect phosphate colorimetrically. The method is based on the formation of a complex between phosphate and molybdate. This complex is protected from oxidation through adding ascorbic acid. The complex is stable for 4 h after a reaction time of 15 min *(OLSEN and SOMMERS, 1982).* All samples were measured by an Agilent 8453 UV-Visible spectrophotometer using either a flow cell or manual cuvettes.

2.5.2.1 Molybdenum-Blue Method

This method originally published by *MURPHY and RILEY (1962)* is used as a standard method for determination of phosphorus extracted by soil testing. The detection limit is

0.3 mg P L^{-1}. The detailed protocol for the procedure can be found in *OENORM L 1087 (2006)*.

The first step was to produce a stock solution of ammonium heptamolybdate which had to be further diluted (1:10) just before usage to gain the working solution. Additionally a 0.025 M ascorbic acid solution was prepared. For measurement 1 mL of ascorbic acid was mixed with 0.5 mL of sample and then 8 mL working solution were added (the *OENORM* instructions were modified here, the volume ratio was maintained but just half the amount of liquid was used.) For each measurement series the wavelength had to be set to the optimum. The optima for all measurements were close to 710 nm.

2.5.2.2 Modified Molybdenum-Blue Method

Due to the need for a higher sensitivity, a different method to color the extraction solutions was selected. This method allowed for a detection limit of about 25 µg P L^{-1}.

The method of *MURPHY and RILEY (1962)* was modified accordingly: while the four solutions were prepared with the identical concentrations as in the original, the volumes mixed to prepare the working solution were changed. 10 mL of 2.5 M H_2SO_4 was combined with 3 mL of 0.032 M ammonium molybdate, 1 mL of 0.006 M potassium antimonyltartrate and 6 mL of 0.1 M ascorbic acid. The obtained solution was used for the color reaction, where 1 mL was mixed with 5 mL of sample. After a reaction time of 15 min the samples could be measured at 710 nm.

2.6 Statistical Methods

For basic statistical analysis MS Excel 2007 was used while for computing the analysis of variance and multiple linear regressions SPSS 15.0 for Windows was used. SigmaPlot 11.0 was used to create all the graphical work.

3 Results and Discussion

3.1 Basic Soil Properties

In this chapter a description of the samples with regard to basic soil characteristics will be presented. A summary is given in Table 5a and Table 5b below, the mean, median, standard deviation, minimum and maximum values and also 10% quantile and 90% quantile are presented.

The soil samples used for this experiment represented a wide range of soil characteristics. The pH (KCl) ranged from 4.3 to 7.1, the soils displayed a span from a low base saturation of 21% to a very high one of 97%. Two-thirds of the soils were carbonate free, the remaining soils had carbonate contents ranging from 1.1% to 56% with an average of about 20% $CaCO_3$. The organic carbon was found to range between 0.93% to 4.03% and the C/N ratio of the organic matter varied from 9 to 25 and the N/P ratio ranges from 5 to 63. These ratios are usually given jointly as C/N/P ratio, in soils this is on average 186/13/1*(CLEVELAND and LIPTZIN, 2007).* The texture of the soils showed a wide range. The samples were varying between a high clay content of over 50% to a very high sand content of over 80%. The potential CEC showed an average of 13 $cmol_c\ kg^{-1}$.

The Fe_d (oxidic iron) ranged from 1863 mg kg^{-1} to 42990 mg kg^{-1}. The Fe_o/Fe_d ratio – giving information on the degree of weathering of the iron oxides and therefore on the age of the soil *(LAIR et al., 2009)* – indicated that the selection of soils featured samples with mainly amorphous iron oxides (Fe_o/Fe_d above 0.5) to soils with primarily crystalline iron oxides (Fe_o/Fe_d below 0.5) The ratio P_o/Fe_o was ranging between 0.08 and 0.84.

Soil parameters of particular importance to P solubility, P availability and P extractability are: the prevailing pH in the soil and related to it the $CaCO_3$ content, the distribution of texture, the mineralogical composition, the total surface area, the content of organic matter and also the presence of Fe and Al (hydr-)oxides *(ABDU, N. 2006).* The prevalent combination of these parameters in the soil influences the solubility of phosphates. For example, *ZORN and KRAUSE (1999)* reported that the extraction capacity of the CAL method was affected by $CaCO_3$. It is possible that higher $CaCO_3$ contents increase the pH in the extraction solution and may therefore diminish the effectiveness of the CAL extraction. However, samples which showed reduced extraction capacity could not be identified by their $CaCO_3$ content alone.

Table 5a: Summary of physicochemical soil properties; n=50

	pH (H_2O)	pH (KCl)	[a] EC	[b] OC	$CaCO_3$	C/N (molar)	C/P (molar)	N/P (molar)	[c] KH	Clay	Silt	Sand
			[mS cm^{-1}]	[%]					mL $100g^{-1}$		[%]	
Mean	7.2	6.0	0.65	1.72	5.6	13.0	173	13.6	55.1	22.8	40.1	36.5
Median	7.3	6.0	0.61	1.47	0	11.7	129	11.4	52.3	24.4	46.2	28.1
Standard Dev.	0.5	0.8	0.27	0.74	11.6	3.1	103	9.1	22.1	9.9	16.6	23.8
Minimum	6.1	4.3	0.23	0.93	0	9.0	79	5.4	26.0	4.2	9.1	1.5
10% Quantile	6.5	4.9	0.37	1.02	0	10.4	90	7.8	31.7	12.1	18.2	13.1
90% Quantile	7.9	7.0	1.02	2.67	25.1	15.9	292	22.2	78.0	34.5	59.8	66.3
Maximum	8.0	7.1	1.35	4.03	56.2	25.1	564	63.0	121	53.1	63.6	86.2

[a] EC = electrical conductivity in saturated H_2O extract
[b] OC = organic carbon
[c] KH = amount of water necessary to prepare the H_2O saturation extract

Table 5b: **Summary of physicochemical soil properties; n=50**

	[d] **CEC$_{pot}$**	[e] **BS**	**Ca**	**Mg**	**K**	**Al**	[f] **Fe$_d$**	[f] **Mn$_d$**	[g] **Fe$_o$**	[g] **Mn$_o$**	[fg] **Fe$_o$/Fe$_d$**	[g] **P$_o$/Fe$_o$**
	[cmol$_c$ kg^{-1}]	[% of CEC$_{pot}$]					[mg kg^{-1}]					**(molar)**
Mean	13.0	67	55.3	8.0	2.9	2.3	9770	490	4040	373	0.42	0.31
Median	12.4	66	54.4	7.8	2.5	1.5	8370	450	3270	381	0.42	0.25
Standard Dev.	4.5	21	19.4	3.3	1.7	2.2	6480	197	3320	195	0.14	0.20
Minimum	6.2	21	14.7	3.0	0.5	0.2	1863	67	930	47	0.14	0.08
10% Quantile	7.4	40	31.6	3.9	1.0	0.4	4900	275	1360	143	0.23	0.16
90% Quantile	18.0	95	80.9	13.0	5.7	5.4	14240	704	5710	598	0.55	0.67
Maximum	29.1	97	82.6	15.8	7.4	11.4	42990	1010	21950	821	0.82	0.84

[d] CEC$_{pot}$ = potential cation exchange capacity (determined at pH 8.1)

[e] BS = base saturation

[f] Fe$_d$ and Mn$_d$ = dithionite-extractable Fe and Mn

[g] Fe$_o$, Mn$_o$ and P$_o$ = oxalate-extractable Fe, Mn and P

3.2 Soil P Extractions

3.2.1 Comparing Applied Soil P Extraction Methods

In this chapter the data gained by the soil P extraction methods are displayed in detail. The measured values were processed and prepared statistically in Table 6. The mean, median, standard deviation, minimum and maximum values and also 10% quantile and 90% quantile are given. Average values shown in Table 6 are illustrated graphically in Figure 9. To compare the methods with each other, it was tested how well they correlate. The correlation coefficients with significance level are given in Table 7.

On average, the efficiency of extraction increased along the order of H_2O < $CaCl_2$ < LiCl < Fe-oxide P_i < Olsen < CAL < CAEM < Mehlich 3 < Bray II < Dithionite < Organic P < HCl < Oxalate < Total P (shown in Table 6 and Figure 9). This sequence is similar to findings by other authors (*KULHÁNEK et al., 2009b, CSATHÓ et al., 2005, FERNANDES et al., 1999)*.

While the H_2O, $CaCl_2$ and LiCl extractions extracted an average P amount below 10 mg kg^{-1}, the averages of Fe-oxide P_i, Olsen, CAL and CAEM were also in the same range of around 100 mg kg^{-1}. Mehlich 3 and Bray II obtained about the same average magnitude (below 200 mg kg^{-1}) while Dithionite, Organic P and HCl averaged between 200 and 300 mg kg^{-1}. The mean values of Oxalate and Total P amounted to 530 and 830 mg kg^{-1}, respectively.

The widest range of measured values by the same extraction method was detected for Bray II where the highest value was of 201-fold greater magnitude than the lowest measured value that is 3.13 mg kg^{-1} vs. 628 mg kg^{-1}, respectively. The narrowest range was detected for the HCl extraction method, where the maximum extracted P (622 mg kg^{-1}) was less than five times higher than the lowest value (129 mg kg^{-1}). *SAGGAR et al. (1999)* discussed the advantage of extraction methods producing a greater range within the samples, stating that a categorization in P status groups may be more easily achieved. This is especially important in routine soil testing when results provide the basis for fertilization recommendations.

As expected, the lowest extractable amount of phosphorus from soil was found by the H_2O extraction method and the highest amount was measured by the extraction method for the total P content (c.f. Table 7 Figure 9). *KULHÁNEK et al. (2007*) stated that $CaCl_2$ may extract lower amounts of P than the H_2O method due to formation of Ca-phosphate. The data of our experiment showed different results, probably due to the application of a saturation water extract. Also, concentrations for a H_2O extract found by *MARSCHNER (1995)* ranged from 0.8 to 8.0 mg kg^{-1} while our results showed lower values of 0.03 to 1.79 mg kg^{-1} which may be for the same reason.

The total P values in our samples ranged from 298 to1680 mg kg^{-1}, reflecting a diverse range of soils. By comparison *CROSS and SCHLESINGER (1995)* found total P values from 64 to 908 mg kg^{-1} in 88 different soils globally.

ZBÍRAL and NĚMEC (2002) measured for Mehlich 3 similar values as in our study ranging from 4 to 643 mg kg^{-1} with an average at 107 mg kg^{-1} over a very broad range of soils. But in general, it was found that a comparison with other studies entails some problems; soils in other studies are found to be very different regarding physicochemical parameters (e.g. tropical soils *BORTOLON and GIANELLO, 2012, MAMO et al., 1996*); other studies applied a variety of other crops *(KUMAR et al, 1994)* or tested the influence of various fertilizer applications on P extraction methods *(MENON et al., 1989a, MENON et al., 1991)*.

Table 6: **Comparison of the extractable P by the 14 extraction methods [mg kg^{-1}]; n=50, Dithionite n= 48**

	H_2O	$CaCl_2$	LiCl	[a] Fe-oxide P_i	Olsen	[b] CAL	[c] CAEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate	Total P
							[mg kg^{-1}]							
Mean	0.26	2.58	6.79	46.2	49.6	99.3	102	140	183	209	300	315	529	825
Median	0.12	1.52	4.95	41.3	41.4	76.9	94.2	110	158	179	308	304	488	844
Standard Dev.	0.35	2.31	6.33	27.2	27.0	62.6	56.5	106	127	126	132	125	225	271
Minimum	0.03	0.10	b.d.	5.58	10.8	17.8	20.5	27.2	3.13	44.4	54.4	129	179	298
10% Quantile	0.04	0.74	1.64	18.3	21.7	40.3	37.5	46.5	67.0	76.1	134	158	320	449
90% Quantile	0.56	5.63	12.7	86.1	80.7	182	182	256	347	381	459	481	770	1150
Maximum	1.79	10.5	34.8	122	124	267	246	540	628	607	716	622	1300	1680

[a] Fe-oxide P_i = iron oxide impregnated filter

[b] CAL = calcium acetate lactate

[c] CAEM = cation and anion exchange membrane

As mentioned in the beginning of this chapter, the magnitude of the average extracted phosphorus by the 14 methods is shown in Figure 9. Additionally, the average P uptake by the plants is given in the first column. This comparison illustrates that the weaker extraction methods (i.e. H_2O, $CaCl_2$, LiCl) were in the range of the average P uptake by plants, whereas the other extraction methods extracted much higher P amounts. It is notable that the oxalate extraction method was closest to Total P amounts in the soil samples. *MENON et al. (1989)* found that measured values of Fe-oxide P_i and Olsen were about the same magnitude, which is in agreement with the results obtained in our study and displayed in Figure 9.

Plants and other organisms mainly assimilate phosphorus dissolved in the soil solution. Due to its low solubility, the concentration of dissolved phosphorus in the solution is generally low (below 5 µmol) *(CONDRON and TIESSEN, 2005), BLUME et al., (2010)* listed a concentration of 0.2 to 0.8 mg P L^{-1}. Approximately that amount was extracted by our water saturation extraction. *EMSLEY (2001)* stated that the concentration in the soil solution will at any given time hold only about 1% of phosphorus essential to a healthy plant growth. In our study, the average amount of P taken up by the plants was 4.55 mg kg^{-1}, while the H_2O extraction method extracted 0.26 mg kg^{-1} on average. Here, the P in soil solution was more than 5% of the average plant uptake.

Figure 9 displays also that the average organic P amounted to about 50% of the total P in the given soil samples which is in agreement with *CONDRON and TIESSEN (2005)* who stated a common range of 35-65%.

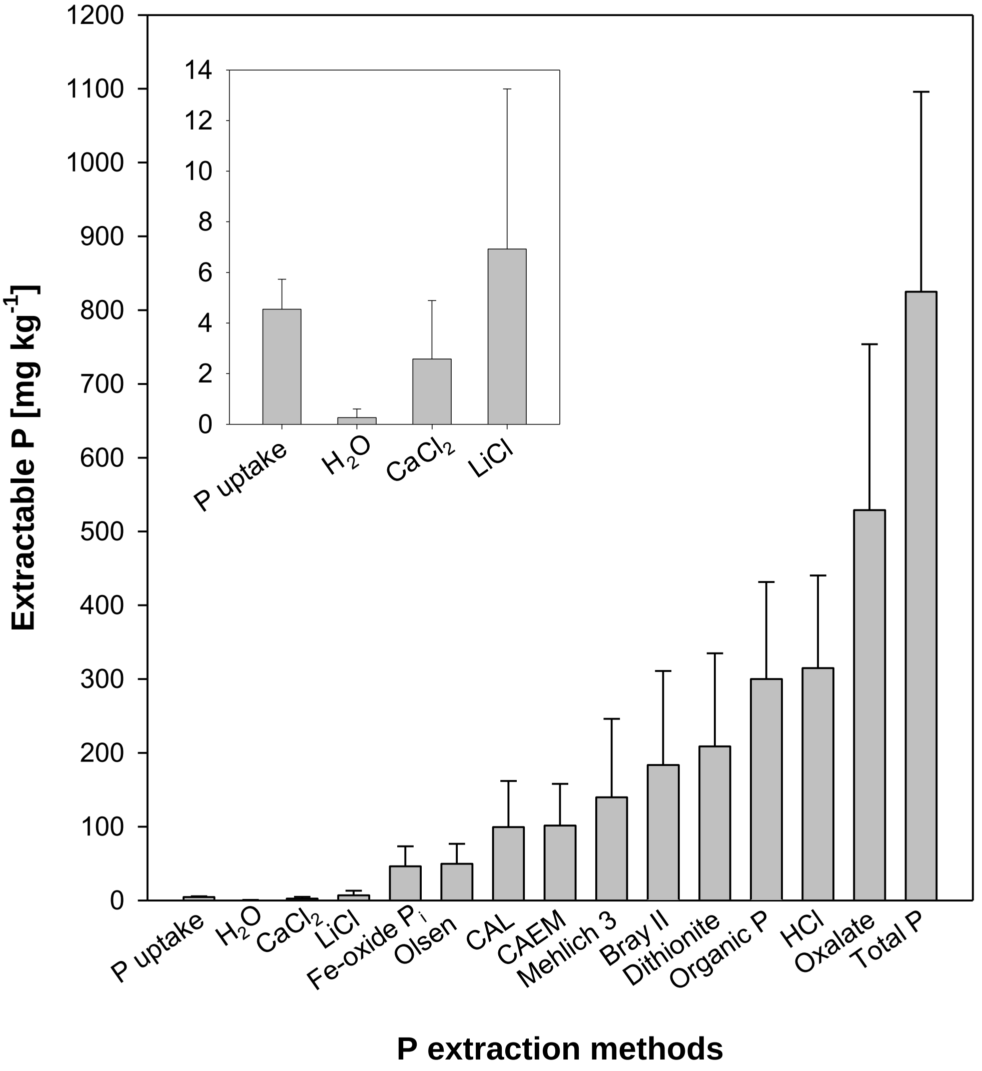

Figure 9: **Comparison of applied extraction methods by the average amount of extracted P and standard deviation. Abbreviations: Fe-oxide P_i = iron oxide impregnated filter paper, CAL = calcium acetate lactate, CAEM = cation and anion exchange membrane**

From Table 7, it can be perceived as an overall trend that most extraction methods correlated well with each other. Two extraction methods did not follow this trend: Organic P, which only correlated with the extraction methods Dithionite, Oxalate and Total P positively and with $CaCl_2$ negatively, and Total P, which correlated (positively) with only half of the methods (Olsen, CAL, CAEM, Dithionite, Organic P, HCl, and Oxalate). Moreover, it was notable that the correlation coefficients between the weaker extraction methods, i.e. H_2O, $CaCl_2$ and LiCl, and the other extraction method declined with increasing extracting intensity of the other methods. The Dithionite extraction method did not correlate with any of these weaker extraction methods, a similar picture could be noted for Oxalate.

The highest correlation coefficient was found between Bray II and Mehlich 3 (0.944), the lowest was determined for Total P and $CaCl_2$ (being close to 0.000). The close correlation of Bray II and Mehlich 3 was most likely found due to their similar mechanism to extract the phosphorus (F^- binding on Al and releasing phosphate). Throughout the study the results by these two extraction methods exhibited similarity.

Interesting is that the H_2O method best correlated with the LiCl while the $CaCl_2$ method was closest correlated with the Fe-oxide P_i. The close correlation by CAEM and Fe-oxide P_i was expected as these methods are based on the same mechanism. Equally, the highest correlation coefficient for Organic P and Oxalate was found with Total P as these three methods (also) extract organic bound phosphorus.

Table 7: Correlation coefficients between the extraction methods, significance in * *p* < 0.05; ** *p* < 0.01; * *p* < 0.001**

	H_2O	$CaCl_2$	LiCl	[a]Fe-oxide P_i	Olsen	[b]CAL	[c]CAEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate
$CaCl_2$	0.795 ***												
LiCl	0.851 ***	0.771 ***											
[a]Fe-oxide P_i	0.644 ***	0.813 ***	0.686 ***										
Olsen	0.574 ***	0.657 ***	0.646 ***	0.888 ***									
[b]CAL	0.509 ***	0.556 ***	0.732 ***	0.663 ***	0.801 ***								
[c]CAEM	0.722 ***	0.721 ***	0.752 ***	0.868 ***	0.849 ***	0.661 ***							
Mehlich 3	0.437 **	0.701 ***	0.652 ***	0.865 ***	0.837 ***	0.761 ***	0.693 ***						
Bray II	0.409 **	0.643 ***	0.649 ***	0.810 ***	0.792 ***	0.826 ***	0.658 ***	0.944 ***					
Dithionite	0.194	0.193	0.173	0.528 ***	0.664 ***	0.342 *	0.607 ***	0.394 **	0.367 **				
Organic P	-0.073	-0.337 *	-0.164	-0.209	-0.047	-0.048	-0.098	-0.210	-0.152	0.378 **			
HCl	0.327 *	0.289 *	0.447 **	0.516 ***	0.727 ***	0.740 ***	0.622 ***	0.448 **	0.505 ***	0.598 ***	0.104		
Oxalate	0.293 *	0.216	0.286 *	0.538 ***	0.740 ***	0.564 ***	0.551 ***	0.497 ***	0.519 ***	0.788 ***	0.475 ***	0.695 ***	
Total P	0.165	-0.040	0.157	0.214	0.436 **	0.400 **	0.359 *	0.139	0.212	0.675 ***	0.765 ***	0.680 ***	0.813 ***

[a] Fe-oxide P_i = iron oxide impregnated filter paper

[b] CAL = calcium acetate lactate

[c] CAEM = cation and anion exchange membrane

3.2.2 ICP versus Photometer

Figure 10 shows the difference of measurement when using ICP-OES and the colorimetric method (molybdenum blue method measured by photometer) performed as described in *OENORM L 1087 (2006)*. As mentioned in chapter 2.5.1, the photometer is only capable of detecting phosphate because it is dependent on the formation of a molybdenum blue complex. *SEELING and JUNGK (1996)* found that the $CaCl_2$ method extracts organic P that is taken up and readily utilized by plants. However, this fraction of organic phosphorus – phytate soil phosphorus – is immeasurable by the molybdenum blue method. Even though phytate soil phosphorus is highly plant available, *STEFFENS et al. (2010)* found that routine soil tests are only limitedly able to extract and detect this fraction of soil phosphorus. . Conversely, according to *KUO (1996)*, the colorimetrical method is preferable for samples containing low amounts of phosphorus or a high proportion of organic phosphorus; ICP measurement might overestimate the extractable P due to an oxidation of organic P through high plasma temperatures at measurement. *MALLARINO (2003)* found that ICP measurements determined higher P amounts than the photometer, and found a correlation coefficient of 0.84 for Mehlich 3 measured by both ICP and photometer.

In order to determine differences due to the type of measurement for the samples at hand, for four methods (H_2O, $CaCl_2$, Olsen, CAL) all 50 samples were measured by both analytical techniques. The data showed similar results as reported by *PIERZYNSKI et al. (2011)*; a very close correlation between ICP and photometer was observed for all four extraction methods (see Figure 10). Furthermore, the values measured by ICP were slightly higher than the ones detected by photometer. *PIERZYNSKI et al. (2011)* found a higher variability between the two detection methods when the samples contained only low P contents (below 60 mg kg^{-1}); this is not in agreement with the data presented in our study.

As values measured by the two analytical techniques showed only little difference, a double measurement for all methods was considered unnecessary. Coefficients of determination ranged between 0.935 for Olsen and 0.996 for CAL. For the other methods, the P contents were only determined by one of the analytical techniques, i.e. either ICP-OES of photometer (cf. Table 1).

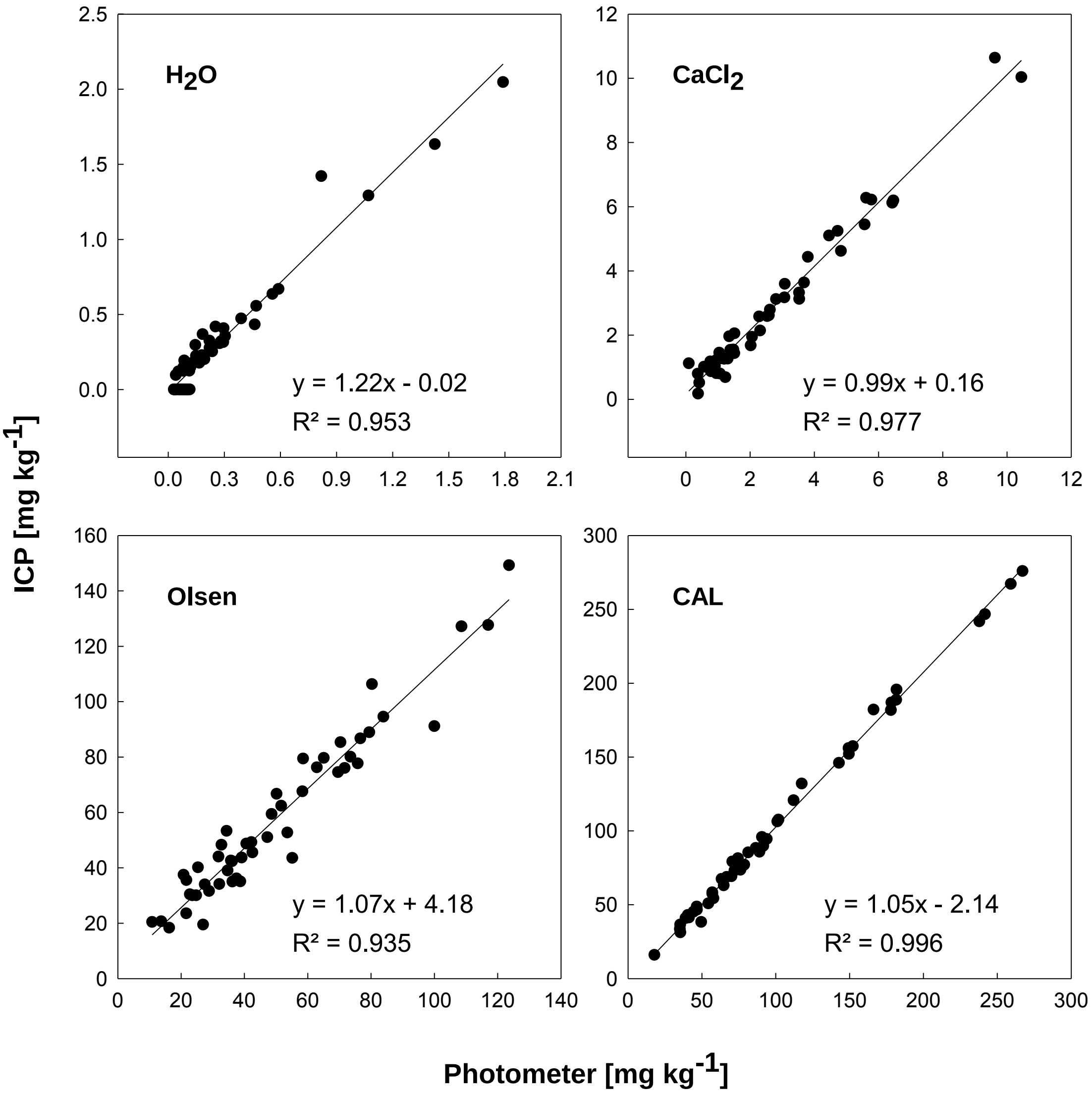

Figure 10: **A comparison of measurement by ICP-OES and by photometer on the basis of coefficients of determination of four soil P extraction methods. Abbreviations: CAL= calcium acetate lactate**

3.3 Correlating Soil P Extraction Data with Soil Parameters

In this chapter, correlations for P extractions and soil parameters were calculated. Table 8a and 8b show the correlation coefficients for the soil parameters and the P estracted by the different extraction methods. In addition, correlation coefficients of soil parameters and the total P uptake by the plants are presented in these tables.

As a next step, in Table 9 the 50 soil samples were grouped according to pH (KCl), the organic carbon and clay content. The three subdivisions of pH (KCl) were selected at pH lower than 5.5, from 5.5 to 6.6 and pH higher than 6.6. The organic carbon content was subdivided to a group below 1.2%, a group from 1.2% to 2% and one above 2% organic carbon content. Also the clay content was split into three groups of clay content below 17%, ranging from 17% to 28% and one that was above 28%. The classification ranges are based on *BLUM et al. (1996)* and modified to better fit the sample data. For each P extraction method and grouping the mean values and the standard deviations were calculated. Subsequently these calculated values were compared in an ANOVA. The Levene test was used to assure homogeneity of variances. As a standard post hoc test the Duncan test disclosed significant differences of means (significance level of 0.05). If the Levene test was significant, the Games-Howell test was used instead (significance level of 0.05). A detailed summary is given below in Table 9 where mean values followed by different letters are significantly different.

As shown in Table 8a and 8b soil parameters and the P uptake by plants (in mg m^{-2}) yielded only two significant results: $CaCO_3$ and K correlated significantly negatively. This indicated that besides the two parameters just mentioned, none of the soil properties had a major impact on the uptake of P by the plants. Generally, an increasing amount of $CaCO_3$ may decrease the amount of plant available P *(MING, 2006)*. This is likely caused by sorption and co-precipitation of phosphate on calcite surfaces.

The pH was negatively correlated with $CaCl_2$, Fe-oxide P_i, Olsen, CAEM, Mehlich 3, Bray II and Dithionite. Due to the relation of pH with $CaCO_3$, base saturation (BS) and exchangeable Ca the results were corresponding. The CAL method was found to overestimate the decrease in plant availability with increasing $CaCO_3$, as the pH of the extraction solution may be raised by the calcium carbonate of the soil *(ZORN and KRAUSE, 1999, ZBÍRAL and NĚMEC 2002)*. As an alternative *ZORN and KRAUSE (1999)* suggested the use of the Olsen extract, *ZBÍRAL and NĚMEC (2002)* proposed the use of Mehlich 3. However, results given in Table 8a and 8b show that CAL did not correlate significantly with the amount of $CaCO_3$; however, the Olsen extraction displayed a negative correlation with this parameter, and the correlation coefficient for

Mehlich 3 indicated a similar relation. Equally, Fe-oxide P_i and CAEM and Dithionite extracted significantly ($p < 0.001$) lower P when the $CaCO_3$ amount increased. *ZBÍRAL (2000)* argues that acidic extraction methods for soil P are highly affected by the prevailing pH during extraction. The results gained by the ANOVA (given in Table) revealed that the mean values for Fe-oxide P_i, CAEM and Dithionite were significantly lower for the third group of pH above 6.6. However, as the three extraction methods are not acidic extraction methodsthese results may not indicate a pH dependency by these three methods but propose that our samples of higher pH (and $CaCO_3$ content) had indeed less available P for plant uptake.

ZHENG and ZHANG (2012) state that soil texture and soil particle size distribution has a very high influence on soil phosphorus fractions. The authors attribute the impact of texture to its influence on the microbial biomass and activity in soils. All fractions of P that were affected by microbial activity were equally affected by texture, and that also implied extraction by soil P extraction methods. Investigations by *FERNANDES et al. (1999)* showed that Olsen, Fe-oxide P_i and CAEM were less dependent on soil texture, while results of our experiment indicated a significant correlation ($p < 0.01$) with texture, except for CAEM, indicating that CAEM was not texture dependent. A positive correlation of HCl with sand content as found by *MENON et al. (1989b)* was not revealed by the data at hand. Furthermore, only the organic P content was correlated negatively with the sand content and positively with the clay content (all other extraction methods that correlated with texture showed the opposite trend), suggesting protection of organic P pools in the clay fraction. The weaker extraction methods correlated negatively with the silt and clay content and positively with sand content; conversely, *O'HALLORAN et al. (1987)* found that low sand content correlated with higher amounts of extractable P by methods extracting the labile forms of P. Investigation of the extracted P values in an ANOVA given in Table 9 disclosed that for $CaCl_2$, Fe-Oxide P_i and CAEM, mean values of clay content up to 28% were higher than for clay content >28%. For Mehlich 3 and Bray II the low clay samples < 17% had a significantly higher average value and standard deviation. Organic P and Total P showed the opposite trend (cf. Table 9).

Oxalate and dithionite-extractable Mn and Fe contents correlated better with the stronger extraction methods, e.g. Dithionite, Organic P, HCl, Oxalate and Total P. Whereas with the Fe_o/Fe_d ratio all methods correlated significantly except for the weaker extraction methods (i.e. H_2O, $CaCl_2$ and LiCl) and Total P. Bray II only correlated significantly with parameters, when Mehlich 3 was correlated significantly with them.

The parameter of organic carbon only correlated with the methods of Organic P, Oxalate and the Total P, showing that only these extracting methods were able to extract significant amounts of P from the organic pool. Results obtained by the ANOVA in Table 9 show similar outcomes. As expected, values for Organic P and Total P revealed a positive relation with increasing OC amount. The more organic carbon, the more organic phosphorus was extracted. Additionally Fe-oxide P_i obtained significant differences, but the lowest value was found for the highest OC amounts.

It is notable that correlation coefficients of Organic P and Total P were inverse compared to the other extraction methods (e.g. for C/N, C/P, Clay, Sand, CEC_{pot}, Mg). Thus, if other extraction methods correlated significantly positively, they correlated significantly negatively. In general it was perceptible that the Total P correlation coefficients were only significant when the Organic P was also significant. One can conclude that these two extraction methods extracted a completely different pool (the organic P) in soils, not corresponding to the other methods.

KUMAR et al. (1994) found that not only soil properties but also the composition of fertilizers is likely to change results on which method is most suitable to determine plant available phosphorus. Due to fertilizer residues and their variable solubility, these effects may even have overlaid soil property influences. In our experiment different soil fertilizers were used beforehand, however their influence could not be considered as this would have gone beyond the scope of this work.

Table 8a: Correlation coefficients of soil P extraction methods and soil properties, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	pH (H_2O)	pH (KCl)	[a] EC	[b] OC	$CaCO_3$	C/N (molar)	C/P (molar)	N/P (molar)	[c] KH	Clay	Silt	Sand
H_2O	-0.174	-0.111	0.154	-0.089	-0.234	0.062	0.014	-0.016	0.010	-0.011	-0.161	0.119
$CaCl_2$	-0.435 **	-0.348 *	0.387 **	-0.223	-0.341 *	0.452 ***	0.223	0.010	-0.359 *	-0.422 **	-0.462 ***	0.500 ***
LiCl	-0.125	0.024	0.407 **	-0.067	-0.238	0.184	0.166	0.077	-0.155	-0.237	-0.291 *	0.301 *
[d] Fe-oxide P_i	-0.471 ***	-0.423 **	0.272	-0.162	-0.478 ***	0.414 **	0.191	-0.010	-0.329 *	-0.394 **	-0.500 ***	0.515 ***
Olsen	-0.343 *	-0.319 *	0.219	0.076	-0.363 **	0.268	0.170	0.020	-0.148	-0.242	-0.463 ***	0.427 **
[e] CAL	-0.027	0.110	0.267	0.142	-0.143	0.129	0.262	0.171	-0.150	-0.216	-0.387 **	0.360 *
[f] CAEM	-0.298 *	-0.286 *	0.218	-0.104	-0.500 ***	0.127	0.182	0.141	-0.169	-0.195	-0.273	0.274
Mehlich 3	-0.390 **	-0.308 *	0.391 **	-0.081	-0.338 *	0.555 ***	0.299 *	0.030	-0.402 **	-0.549 ***	-0.574 ***	0.630 ***
Bray II	-0.290 *	-0.200	0.322 *	-0.103	-0.380 **	0.455 ***	0.214	-0.030	-0.405 **	-0.512 ***	-0.524 ***	0.579 ***
Dithionite	-0.387 **	-0.448 **	-0.188	0.043	-0.466 ***	-0.085	-0.238	-0.194	-0.108	-0.172	-0.246	0.251
Organic P	0.266	0.193	-0.355 *	0.376 **	0.201	-0.440 **	-0.582 ***	-0.420 **	0.489 ***	0.427 **	0.268	-0.364 **
HCl	0.077	0.068	0.006	0.213	-0.163	-0.134	0.072	0.081	0.027	-0.029	-0.118	0.097
Oxalate	-0.104	-0.144	-0.117	0.291 *	-0.179	-0.059	-0.167	-0.171	0.127	-0.010	-0.222	0.164
Total P	0.221	0.164	-0.267	0.392 **	0.070	-0.413 **	-0.356 *	-0.212	0.370 **	0.293 *	0.142	-0.218
P uptake	-0.131	-0.149	0.211	0.037	-0.308 *	0.000	0.069	0.018	0.093	-0.016	-0.088	0.069

[a] EC = electrical conductivity in saturated H_2O extract

[b] OC = organic carbon

[c] KH = amount of water necessary to prepare the H_2O saturation extract

[d] Fe-oxide P_i = iron oxide impregnated filter paper

[e] CAL = calcium acetate lactate

[f] CAEM = cation and anion exchange membrane

Table 8b: Correlation coefficients of soil P extraction methods and soil properties, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	^{g} **CEC$_{pot}$**	^{h} **BS**	**Ca**	**Mg**	**K**	**Al**	^{i} **Fe$_d$**	^{i} **Mn$_d$**	^{j} **Fe$_o$**	^{j} **Mn$_o$**	^{ij} **Fe$_o$/Fe$_d$**	^{j} **P$_o$/Fe$_o$**
H_2O	-0.020	-0.129	-0.200	0.029	0.551 ***	0.031	0.010	0.241	0.051	0.294 *	0.199	-0.005
$CaCl_2$	-0.312 *	-0.379 **	-0.411 **	-0.315 *	0.518 ***	0.173	-0.106	0.003	-0.074	0.093	0.232	0.122
LiCl	-0.205	-0.040	-0.102	0.005	0.586 ***	0.189	-0.091	0.108	-0.044	0.160	0.196	0.174
^{d} **Fe-oxide P_i**	-0.136	-0.519 ***	-0.529 ***	-0.370 **	0.241	0.064	0.076	0.141	0.186	0.238	0.522 ***	0.075
Olsen	0.070	-0.402 **	-0.408 **	-0.322 *	0.226	-0.077	0.146	0.099	0.307 *	0.193	0.627 ***	0.091
^{e} **CAL**	-0.064	0.031	0.036	-0.173	0.274	-0.005	-0.096	0.046	0.016	0.079	0.351 *	0.316 *
^{f} **CAEM**	0.004	-0.382 **	-0.414 **	-0.221	0.351 *	0.138	0.173	0.252	0.327 *	0.372 **	0.561 ***	-0.100
Mehlich 3	-0.282 *	-0.429 **	-0.423 **	-0.418 **	0.251	0.075	-0.155	-0.064	-0.054	0.041	0.427 **	0.329 *
Bray II	-0.274	-0.324 *	-0.310 *	-0.373 **	0.204	0.018	-0.147	0.062	-0.044	0.141	0.405 **	0.294 *
Dithionite	0.243	-0.556 ***	-0.573 ***	-0.201	0.012	-0.168	0.597 ***	0.337 *	0.757 ***	0.457 ***	0.573 ***	-0.362 **
Organic P	0.529 ***	0.135	0.086	0.452 ***	-0.156	-0.579 ***	0.558 ***	0.536 ***	0.370 **	0.352 *	-0.285 *	0.069
HCl	0.176	0.021	0.022	-0.030	0.065	-0.208	0.296 *	0.100	0.473 ***	0.068	0.526 ***	-0.016
Oxalate	0.353 *	-0.243	-0.264	0.018	-0.063	-0.399 **	0.455 ***	0.226	0.597 ***	0.289 *	0.486 ***	0.091
Total P	0.515 ***	0.075	0.037	0.325 *	-0.113	-0.534 ***	0.583 ***	0.433 **	0.592 ***	0.302 *	0.173	0.005
P uptake	-0.131	-0.149	0.211	0.037	-0.308 *	0.000	-0.053	-0.078	0.093	-0.016	-0.088	0.069

[d] Fe-oxide P_i = iron oxide impregnated filter paper

[e] CAL = calcium acetate lactate

[f] CAEM = cation and anion exchange membrane

[g] CEC_{pot} = potential cation exchange capacity (determined at pH 8.1)

[h] BS = base saturation

[i] Fe_d and Mn_d = dithionite-extractable Fe and Mn

[j] Fe_o, Mn_o and P_o = oxalate-extractable Fe, Mn and P

Table 9: The mean values ± standard deviation if grouped according to the pH (KCl), organic carbon and clay content, compared in an ANOVA.

	H_2O	$CaCl_2$	LiCl	[a] Fe-oxide P_i	Olsen	[b] CAL	[c] CAEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate	Total P
[d] pH < 5.5	0.26±0.26 a	3.13±2.59 a	5.76±4.17 a	**52.7±24.0 a**	53.2±23.4 a	83.9±42.1 a	**108±46.8 a**	153±96.0 a	186±105 a	**259±136 a**	296±166 a	293±121 a	537±275 a	794±342 a
pH 5.5 to 6.6	0.30±0.42 a	2.87±2.33 a	7.90±6.12 a	**55.0±28.7 a**	55.1±30.2 a	103±62.0 a	**125±51.5 a**	156±129 a	205±137 a	**230±118 a**	258±107 a	332±130 a	529±227 a	788±264 a
pH > 6.6	0.21±0.36 a	1.49±1.53 a	6.69±8.73 a	**26.5±19.3 b**	38.0±25.4 a	115±82.7 a	**63.4±57.8 b**	101±81.5 a	153±144 a	**123±77.3 b**	360±88.2 a	321±130 a	518±155 a	913±271 a
[e] OC < 1.2%	0.18±0.15 a	2.59±1.75 a	5.20±3.82 a	**48.0±21.6 ab**	43.5±17.6 a	80.6±43.1 a	103±45.5 a	119±64.1 a	162±72.9 a	201±76.9 a	**206±78.5 b**	307±125 a	426±141 a	**688±234 b**
OC 1.2% to 2.0%	0.45±0.55 a	3.78±3.16 a	10.03±9.60 a	**57.7±28.3 a**	58.2±28.2 a	104±63.1 a	122±59.7 a	190±118 a	233±130 a	239±110 a	**297±121 a**	290±107 a	557±257 a	**783±230 b**
OC > 2.0%	0.17±0.18 a	1.67±1.46 a	5.55±3.60 a	**36.3±27.6 b**	47.8±31.3 a	109±73.5 a	85.3±59.1 a	118±114 a	163±151 a	194±161 a	**373±129 a**	340±140 a	586±234 a	**959±274 a**
[f] clay < 17%	0.25±0.25 a	**3.67±2.52 a**	7.92±5.07 a	**59.4±28.4 a**	58.8±28.2 a	111±68.4 a	**115±49.6 a**	**207±132 a**	**248±151 a**	235±132 a	**209±118 b**	301±134 a	527±289 a	**677±277 b**
clay 17% to 28%	0.34±0.48 a	**2.58±2.28 a**	7.68±8.43 a	**46.8±22.9 a**	49.4±20.7 a	98.3±62.2 a	**111±55.2 a**	**121±66.3 b**	**180±96.3 ab**	230±115 a	**340±117 a**	358±104 a	561±172 a	**957±245 ab**
clay > 28%	0.15±0.21 a	**1.06±0.82 b**	3.92±2.93 a	**27.0±20.7 b**	37.2±30.4 a	84.9±56.0 a	**69.0±58.6 b**	**74.3±50.8 b**	**99.6±78.4 b**	146±122 a	**368±103 a**	272±133 a	485±201 a	**838±200 a**

[a] Fe-oxide P_i = iron oxide impregnated filter paper

[b] CAL = calcium acetate lactate

[c] CAEM = cation and anion exchange membrane

[d] pH < 5.5 n = 18; pH 5.5 to 6.6 n = 18; pH > 6.6 n = 14

[e] OC = organic carbon < 1.2% n = 15; organic carbon 1.2% to 2.0% n = 15; organic carbon > 2.0% n = 20

[f] clay < 17% n = 18; clay 17% to 28% n = 19; clay > 28% n = 13

3.4 Plant Analysis

Table 10, given below, displays a summary of data collected at harvest or shortly after. While the average dry matter grain yield amounted to 157.4 g m^{-2}, the mean dry matter straw yield was 219.5 g m^{-2}. An average of 301 ears per m^2 was counted and the number of grains per ear was varying between a minimum of 9 and a maximum of 21. An average thousand-seed weight of 35.9 g was calculated. Clearly, these yield parameters were below the average of field-grown spring wheat.

DIEPENBROCK et al. (1999) list an average grain yield for spring wheat at harvest of 643 g m^{-2}. Moreover, typically the thousand-seed weight of spring wheat is higher (i.e. 39.5 g), and stand density is much higher with about 526 ears per m^2; similarly the number of grains per ear reaches a greater average of 30.8.

The minimum value for P in grain was 2950 mg kg^{-1} and the maximum value was 5380 mg kg^{-1}. The minimum content of P in straw was approximately 340 mg kg^{-1} and the maximum content was 2820 mg kg^{-1}. These values were in the range of reported average values for wheat; an average range of 3020 mg kg^{-1} to 5580 mg kg^{-1} is common for wheat grain and the range for wheat straw is 1050 mg kg^{-1} to 1980 mg kg^{-1} *(DIEPENBROCK et al., 1999)*. According to *BLUME et al. (2010)* dry matter wheat grain contains approximately 4000 mg kg^{-1} and straw 1500 mg kg^{-1}. On average, the grain P content was 5 times higher than the straw content (Table 10). The total P uptake was ranging from 460 mg kg^{-1} to 1400 mg kg^{-1} thus showing a 3-fold increase from the lowest to the highest value.

Table 10: **Basic parameters of the plant analysis**

	[a] DM grain yield	[a] DM straw yield	Ears per m^2	Grains per ear	Thousand-seed weight	P content grain	P content straw	Total P uptake
	[g m^{-2}]				[g]	[mg kg^{-1}]		[mg m^{-2}]
Mean	157.4	219.5	301	17	35.9	4190	790	842
Median	159.4	207.7	283	17	36.6	4210	738	855
Standard Dev.	22.6	45.5	35	2	3.4	528	394	193
Minimum	101.9	152.4	264	9	28.4	2950	338	463
10% Quantile	122.6	164.2	283	14	31.4	3420	450	589
90% Quantile	183.0	293.9	358	19	39.5	4920	1100	1030
Maximum	203.8	318.9	433	21	45.1	5380	2820	1400

[a] DM = dry matter

Figure 11 and Figure 12 show each the highest and lowest yield for straw and grain yield, respectively. Pictures were taken just before harvest.

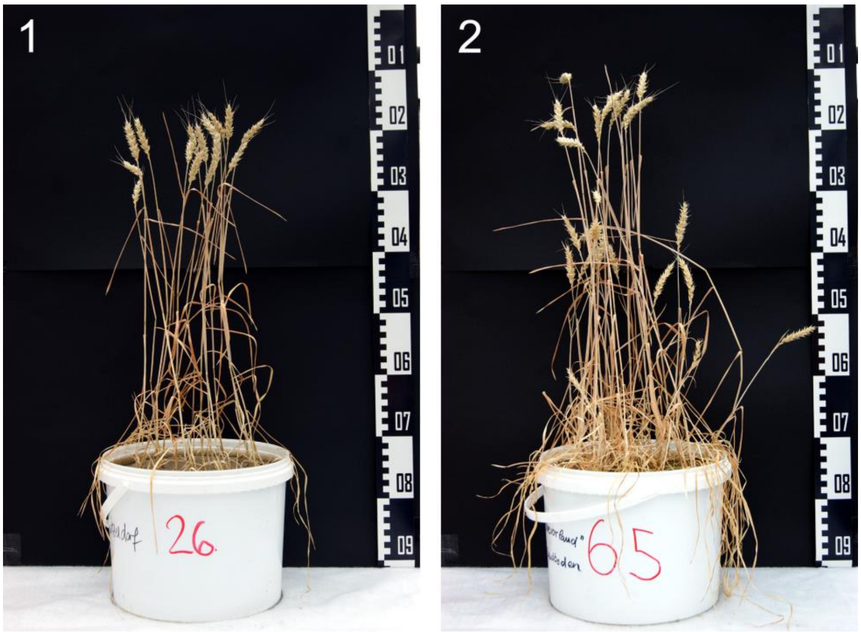

Figure 11: The pots with lowest (1) and highest (2) straw yield.

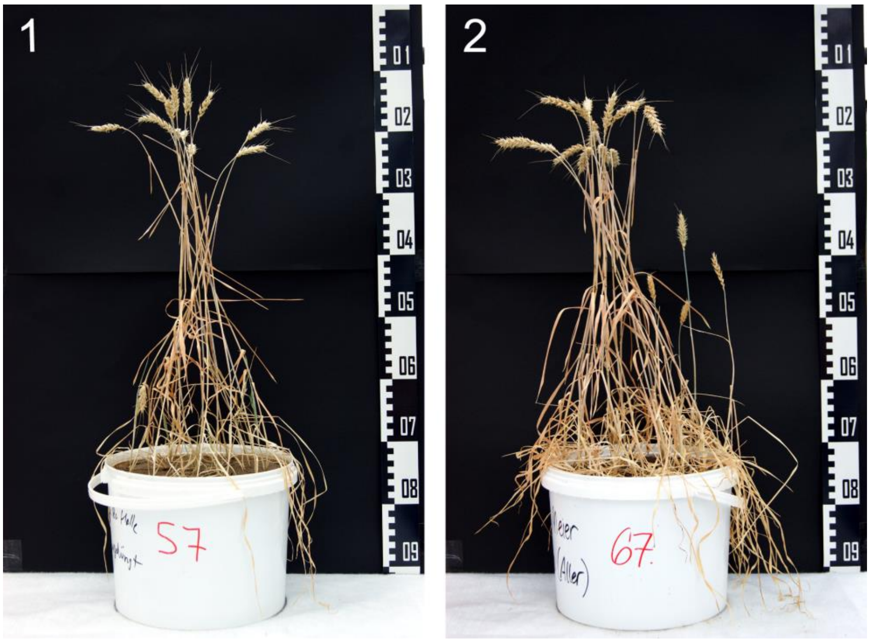

Figure 12: The pots with lowest (1) and highest (2) grain yield.

The following Figure 13 shows the relation between the phosphorus content of grain and straw, respectively and their dry matter yield. While an increasing dry matter straw yield tended to result in a higher phosphorus content of the straw, the grain yield

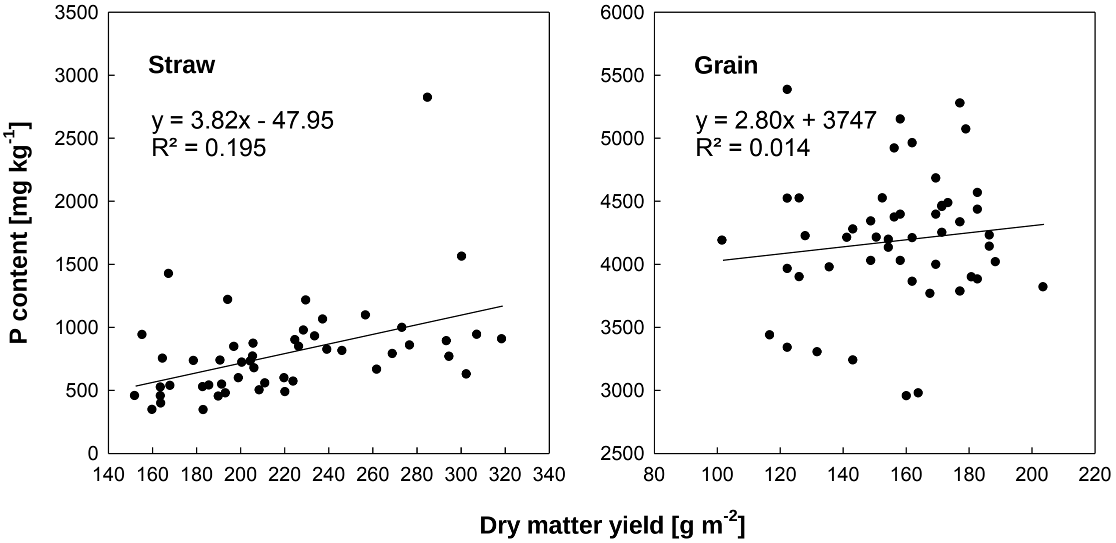

Figure 13: Correlation of dry matter yield of straw and grain with the respective P content measured.

A stepwise multiple linear regression was performed in SPSS. The Figure 14 below shows the contributing share of each of the three harvest parameters to the grain yield variation. The parameters that were taken in account were the number of grains per ear, the number of ears per m^2 and the thousand seed weight. All three parameters showed a similar contribution to grain yield variation. The number of ears per m² explained 34.5% of the grain yield variation, the thousand-seed weight accounted for 32.9%, and the number of grains per ear explained 29.3% of the variation. As discussed in the beginning of this chapter, the yields determined in this study were below average for common spring wheat. It may be assumed that all three parameters contributed equally to the observed low yields.

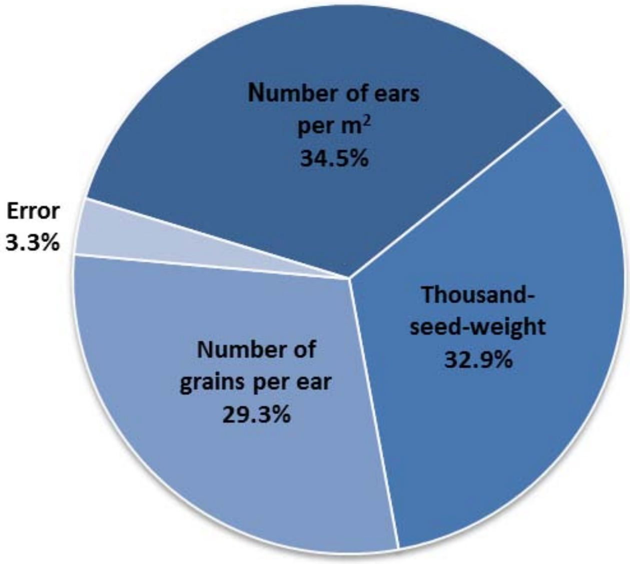

Figure 14: The proportionate contribution of three harvest parameters to grain yield variation.

3.5 Correlating Plant Yield and P Uptake with Extracted P

As a next step, correlation coefficients between the plant data and the P extracted with the different extraction methods were calculated. Correlation coefficients are given in Table 11 below.

In general, straw dry matter yield correlated more significantly with the extracted P by the different soil extraction methods than grain dry matter yield. This is in agreement with *BISSANI et al. (2002)*, who showed generally lower correlation coefficients of grain yield for Mehlich 1, anion exchange resin, anion exchange membrane and Fe-oxide P_i. The observed results may be due to the fact that phosphorus is accumulated in grain seeds in order to provide enough P for germination and the first growing phase when roots are not yet able to take up enough phosphorus. In the plant, P is relatively mobile; therefore, P is not stored in older parts of the plant (i.e. straw) but transported back to the roots and redistributed to plant parts with P demand *(SCHACHTMAN et al., 1998)*. Hence, soil-induced P limitations may be more strongly reflected in the straw compared to the grain.

It is interesting to note that the dry matter yield of grain correlated significantly with the stronger extraction methods, whereas the dry matter yield of straw showed a tendency to correlate less with the strongest extraction methods. The highest correlation coefficient of dry matter grain yield and an extraction method was obtained for the HCl extraction. Similar significance levels were reached by Olsen, CAEM, Dithionite, Oxalate and Total P. For the dry matter straw yield the best correlation coefficient was obtained with the CAEM method ($r = 0.484$, $p < 0.001$). Equally well correlating were methods such as $CaCl_2$, Fe-oxide P_i and Olsen; less but still significant were others such as H_2O, LiCl, CAL, Mehlich 3, Bray II, Dithionite and Oxalate.

Several extraction methods correlated with the parameter ears per m², i.e. $CaCl_2$, Fe-oxide P_i, Olsen, CAL, CAEM, Mehlich 3 and Bray II. This shows that the P availability in our samples may have affected the tillering of the spring wheat. The parameter number of grains per ear was only correlated significantly with the dithionite extraction method, while the thousand-seed weight did not show any significant correlation with the soil extraction methods at all.

SLAFER (2007) stated that the two major yield components, number of grains per m² and average individual grain weight are negatively correlated. Thus, the observed opposite trends of thousand-seed weight and ears per m² are plausible.

Table 11: Correlation coefficients of plant harvest data and extraction methods, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	[a] DM Grain yield	[a] DM Straw yield	Ears per m^2	Grains per ear	Thousand-seed weight
H_2O	0.035	0.425 **	0.251	-0.093	-0.139
$CaCl_2$	0.115	0.467 ***	0.294 *	-0.112	-0.029
LiCl	0.030	0.446 **	0.379 **	-0.203	-0.131
[b] **Fe-oxide P_i**	0.224	0.456 ***	0.301 *	-0.022	0.005
Olsen	0.337 *	0.450 ***	0.336 *	0.098	-0.010
[c] **CAL**	0.204	0.351 *	0.370 **	-0.145	0.155
[d] **CAEM**	0.304 *	0.484 ***	0.375 **	0.014	0.006
Mehlich 3	0.178	0.380 **	0.309 *	-0.023	-0.024
Bray II	0.228	0.400 **	0.346 *	-0.106	0.163
Dithionite	0.304 *	0.297 *	0.212	0.290 *	-0.122
Organic P	0.139	0.145	0.111	0.160	-0.051
HCl	0.364 **	0.266	0.230	0.132	0.124
Oxalate	0.351 *	0.328 *	0.254	0.233	-0.012
Total P	0.345 *	0.249	0.228	0.220	0.039

[a] DM = dry matter
[b] Fe-oxide P_i = iron oxide impregnated filter paper
[c] CAL = calcium acetate lactate
[d] CAEM = cation and anion exchange membrane

Figure 15 shows the correlation of every considered extraction method with the total plant P uptake in mg m^{-2}. The weaker extraction methods achieved a better correlation than the stronger methods. The best coefficient of determination was obtained by the H_2O extraction R^2= 0.337. followed by the $CaCl_2$ extraction method (R^2=0.331)and the CAEM method (R^2=0.24.9). While LiCl and Fe-Oxide P_i revealed a tendency towards correlating, the rest of the methods failed to yield any relation to plant P uptake. Similar results were gained by *KULHÁNEK et al. (2009a)*, finding by far the best correlation with the water extract (R^2=0.66). However, in that study $CaCl_2$ (R^2=0.13) was correlated less than anion exchange membrane extraction (R^2=0.20) and Mehlich 3 (R^2=0.19). These results were based on samples of homogeneous soil types (all loamy) with a pH close to 6.3. The authors suggested that the weak correlation by $CaCl_2$ was a result of Ca-phosphates forming during extraction.

Fe-oxide P_i and CAEM were found to be well correlated with the P uptake by plants (*KUO, 1996)* and were expected to perform better than the other extraction methods, due to their supposed independency of soil properties. This is in agreement with results shown by *SAGGAR et al. (1999)* who found that CAEM extracted higher amounts of soil (available) P than Olsen, and a plant yield prediction was superior to the one by Olsen. *MENON et al. (1988)* claimed that Fe-oxide P_i is an accurate method to determine plant available P and that it is highly independent of soil properties and fertilizer applied. However, *ZHENG and ZHANG (2012)* stated that inconsistent results were observed, deriving from the preparation of the impregnated filter paper. Depending on the type of filter papers, the Fe-oxides may distribute inhomogeneously generating irreproducible extracted P amounts.

In general, our results showed weaker coefficients of determination and lower significance than data presented in most other papers (e.g. *ZORN and KRAUSE, 1999, KULHÁNEK et al., 2009a).* However, this may be explained by the utilization of many different soils with a wide range of basic properties and variable P status rather than applying the method to a limited number of similar soils with altering P levels (due to fertilizer application). Experiments that are based on fewer soils have much less variability in soil parameters. However, their results are very specific for limited soil types and provide less information on a general evaluation of soil P extraction methods and how they are regionally applicable to agricultural soils in Austria and Germany.

Moreover, the plant uptake is also dependent on the plant's ability to take up phosphorus, and not only on the process of supplying by the soil. Important traits in this context are plant age, root system and root age *(HOLFORD, 1997)*. Thus, the plant also influences the amount of plant available P. In this context mycorrhizae are of high agricultural interest. The symbiosis of plants with mycorrhizae increases the efficiency of plants to take up phosphate *(RYAN and RASHID, 2006)* influencing thereby the amount of plant available P.

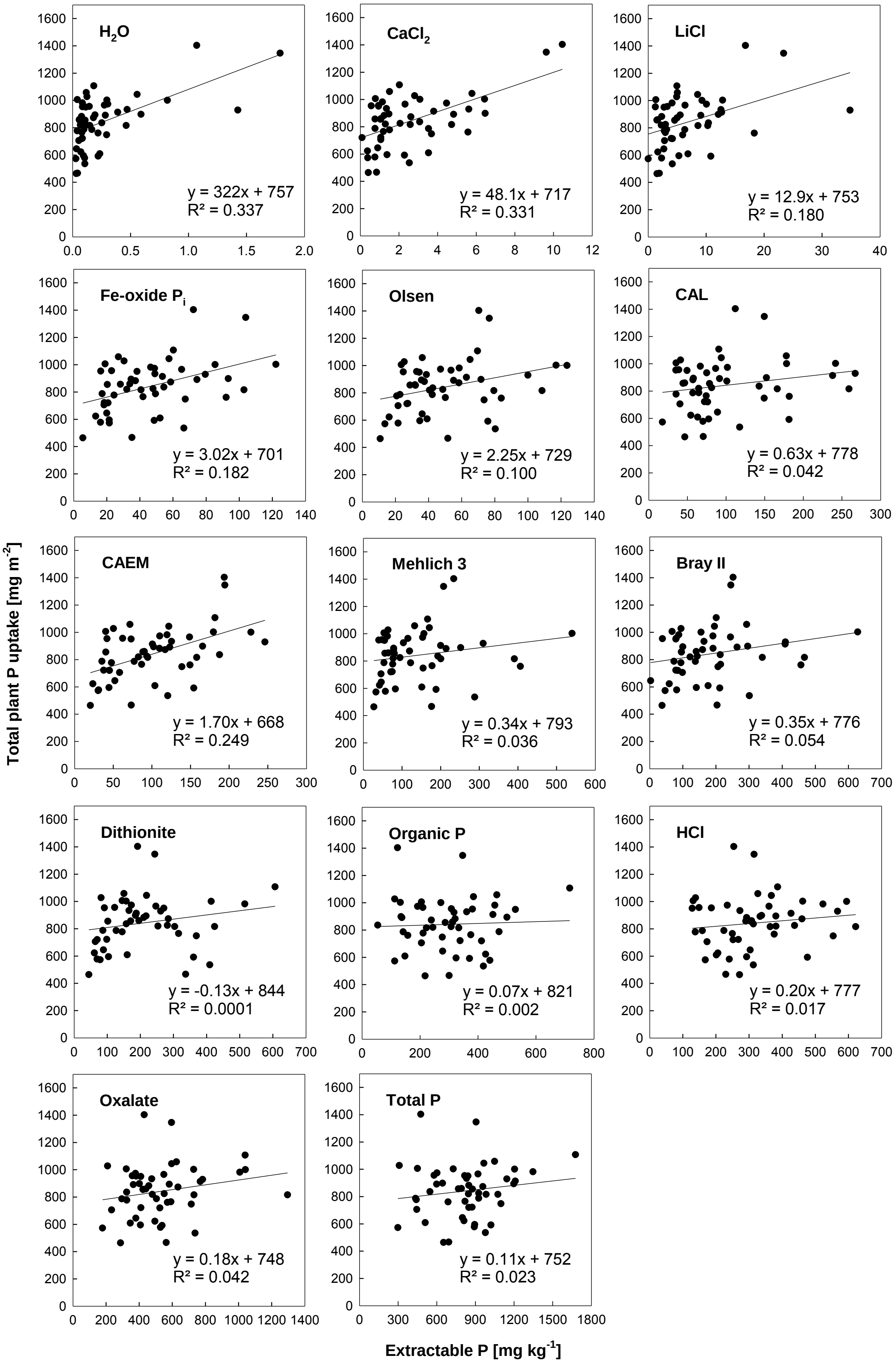

Figure 15: **Regression of the plant P uptake on the extractable P of the different extraction methods. Abbreviations: Fe-oxide P_i = iron oxide impregnated filter paper, CAL = calcium acetate lactate, CAEM = cation and anion exchange membrane**

As mentioned in chapter 3.3 the 50 soil samples were grouped according to their pH (KCl), the organic carbon and clay content. This analysis may provide information on which methods are dependent on the soil properties. The grouping system was chosen based on the classifications by *BLUM et al. (1996)* and modified according to extents of samples, in regard of relatively equal group sizes and more profound differences between the groups per se. The groups of pH (KCl) were selected to be at pH lower than 5.5, from 5.5 to 6.6 and a pH higher than 6.6. The organic carbon content was subdivided to a group below 1.2%, between 1.2% and 2% and one above 2% organic carbon. Also the clay content was split into three groups of clay content below 17%, ranging from 17% to 28% and one that was beyond 28%. After arranging the groups, correlation coefficients between the uptake and the corresponding extractable P by each method were calculated. Results are given in Table 12; a two-tailed significance level was applied to test the significance.

In general, it could be noted that primarily the weaker extraction methods, Fe-oxide P_i and CAEM were correlated in more cases with plant P uptake than the stronger extraction methods. Mehlich 3 and Bray II obtained the similar results over all the correlation coefficients; this is likely a consequence of the similarity of their extraction mechanism. Similarly, the Dithionite, Oxalate and Total P results were corresponding. Furthermore, Fe-oxide P_i and CAEM showed some resemblance regarding significance, yet e.g. at the pH classification they correlated dissimilar with plant P uptake.

Examining the pH groups, the weaker extraction methods (i.e. H_2O, $CaCl_2$, LiCl) were better correlated with the first two groups of pH (below 5.5 and 5.5 to 6.6). In contrast, the Fe-oxide P_i correlated significantly with middle and upper pH groups. The stronger extraction methods correlated significantly only with the last pH group above 6.6, i.e only for calcareous soils. Our results indicate that the weaker extraction methods, being based on water-solubility and ion exchange, performed best in soils around pH 6, where P retention is relatively low, and in more acidic soils, where anion sorption becomes more important *(HOLFORD, 1997).* However, they failed to relate to plant P uptake in calcareous soils, where P is precipitated as calcium phosphate *(TUNESI et al., 1999)*. Obviously, the mechanisms of water solubility and ion exchange are not of primary importance in such soils; plants likely mobilize P (and other nutrients) through acidification of the rhizosphere *(HINSINGER et al., 2003)*. This mechanism, in turn, is more closely simulated by (some of) the stronger extraction methods, which explains their better performance in the high pH soils.

The organic carbon grouping resulted only in the middle (organic carbon in the range of 1.2% to 2.0%) and in the upper group (organic carbon above 2%) in significant correlations. H_2O, $CaCl_2$, LiCl and CAEM were correlated significantly in the middle group. Others, i.e. CAEM, Fe-oxide P_i, Olsen, Dithionite, Oxalate and Total P, obtained significance in the upper group.

For the grouping by clay content, the least amount of significant correlations was detected. Solely the weaker extraction methods and the methods using a sink mechanism were significant. For these extraction methods, significant correlations were found at lower and medium clay contents but not for the grouping with high clay content above 28% clay.

Table 12: **Correlation coefficients of the P uptake by plants and the extractable soil P if samples are grouped according to pH (KCl), organic carbon (OC) or clay content, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$**

	H_2O	$CaCl_2$	LiCl	[a] Fe-oxide P_i	Olsen	[b] CAL	[c] CAEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate	Total P
[d] **pH < 5.5**	0.641 **	0.534 *	0.560 *	0.162	0.126	0.104	0.467 *	-0.003	-0.002	-0.009	0.145	0.033	0.048	0.137
pH 5.5 to 6.6	0.744 ***	0.625 **	0.448	0.501 *	0.266	0.128	0.368	0.085	0.098	0.047	0.031	0.090	0.278	0.175
pH > 6.6	0.383	0.485	0.412	0.546 *	0.503	0.549 *	0.500	0.554 *	0.598 *	0.553 *	0.323	0.357	0.579 *	0.696 **
[e] **OC < 1.2%**	0.319	0.286	0.373	0.258	0.285	0.234	0.330	0.287	0.401	0.153	0.133	0.029	0.216	0.211
OC 1.2% to 2.0%	0.709 **	0.745 ***	0.509 *	0.434	0.226	0.206	0.551 *	0.029	0.057	-0.161	-0.052	0.054	-0.045	-0.036
OC > 2.0%	0.391	0.398	0.240	0.517 *	0.449 *	0.247	0.541 *	0.351	0.387	0.508 *	0.228	0.323	0.601 **	0.468 *
[f] **clay < 17%**	0.715 ***	0.709 ***	0.584 **	0.298	0.210	0.204	0.493 *	0.121	0.133	-0.154	-0.277	0.169	0.003	-0.052
clay 17% to 28%	0.638 **	0.649 **	0.422	0.652 **	0.431	0.185	0.577 **	0.436	0.295	0.358	0.295	-0.094	0.357	0.171
clay > 28%	0.405	0.351	0.159	0.442	0.352	0.220	0.362	0.244	0.391	0.377	0.296	0.025	0.392	0.309

[a] Fe-oxide P_i = iron oxide impregnated filter paper
[b] CAL = calcium acetate lactate
[c] CAEM = cation and anion exchange membrane
[d] pH < 5.5 n = 18; pH 5.5 to 6.6 n = 18; pH > 6.6 n = 14
[e] OC = organic carbon < 1.2% n = 15; organic carbon 1.2% to 2.0% n = 15; organic carbon > 2.0% n = 20
[f] clay < 17% n = 18; clay 17% to 28% n = 19; clay > 28% n = 13

A multiple linear regression was performed in order to determine which other factors most contributed to improve the coefficient of determination for predicting plant P uptake from the amount of P extracted by H_2O and $CaCl_2$. These two methods were selected as they initially correlated best with plant uptake. Stepwise backwards multiple linear regressions were applied to exclude one by one the considered soil parameters (c.f. Table 5a and 5b).

When examining the H_2O extraction method, the Fe_d was the single most contributing factor and increased the R^2 from 0.337 to 0.381 as given in Table 13 .

Table 14 displays data of the multiple linear regression for the $CaCl_2$ extraction method, where the addition of Mn_d and OC content helped to increase the R^2 from 0.331 to 0.481.

Table 13: Factors most contributing to improve the coefficient of determination for predicting plant P uptake from H_2O extractable P, as determined by multiple linear regression

R^2=0.381	**B**	**Standard error**	**Standardized beta**	**Statistical significance**
Constant	769	47.4		0.000
[a] **H_2O-P** [mg kg^{-1}]	353	69.4	0.54	0.000
[b] **Fe_d** [mg kg^{-1}]	0.01	0.004	0.29	0.018

[a] H_2O-P = H_2O-extractable P
[b] Fe_d = dithionite-extractable Fe

Table 14: Factors most contributing to improve the coefficient of determination for predicting plant P uptake from $CaCl_2$ extractable P, as determined by multiple linear regression

R^2=0.481	**B**	**Standard error**	**Standardized beta**	**Statistical significance**
Constant	463	97.8		0.000
[a] **$CaCl_2$-P** [mg kg^{-1}]	56.1	10.4	0.60	0.000
[b] **Mn_d** [mg kg^{-1}]	0.44	0.12	0.41	0.000
[c] **OC** [%]	72.6	32.7	0.25	0.032

[a] $CaCl_2$-P = $CaCl_2$-extractable P
[b] Mn_d = dithionite-extractable Mn
[c] OC = organic carbon

The model of categorizing phosphorus in soil in intensity, quantity and capacity factor allows to assess the soil's P buffering capacity and estimate the P supply for plants over time. The intensity factor determines the readily dissolved or weakly adsorbed phosphorus in the soil, while the quantity factor represents the amount that is not immediately available but will be desorbed and supplied with time. The weakest extraction methods, dilute salt solutions and H_2O extraction, are usually applied to describe the intensity factor of soils *(KULHÁNEK et al., 2008)*. The ratio between quantity and intensity is commonly applied to define P buffering and re-supplying capacity in soils *(RYAN and RASHID, 2006)*.

Figure 16 shows a correlation between plant P uptake on the y-axis and the ratio of quantity factor over intensity factor. Similar to literature, H_2O was chosen as intensity factor while CAEM was chosen as quantity factor (selected because of best correlation with the plant uptake). A positive relation between plant P uptake and the quantity/ intensity ratio was expected. The observed negative correlation may indicate that the quantity factor did not have much impact on the total P uptake by the plants over the course of this (short-term) experiment as the intensity factor was sufficient to cover nutritional necessities by plants. However, in case of a longer test duration, the quantity factor would gain more importance as the resupply of P becomes necessary.

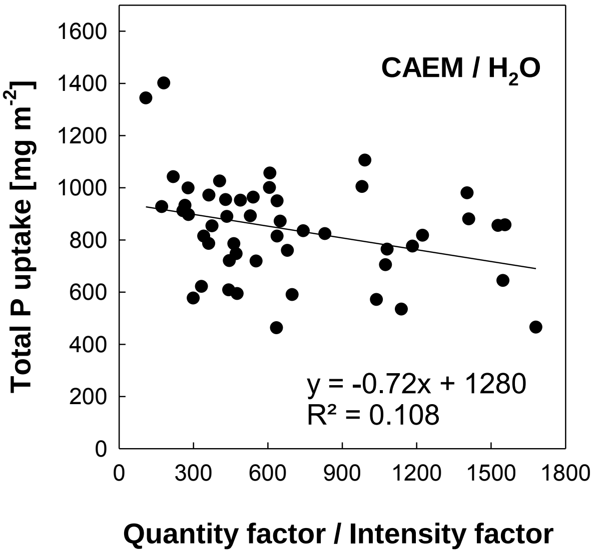

Figure 16: Regression of the plant P uptake on the ratio of quantity factor/ intensity factor. The quantity factor was approximated by CAEM-extractable P, the intensity factor by H_2O extractable P. Abbreviations: CAEM = cation and anion exchange membrane

4 Conclusions and Outlook

The aim of this study was to determine the amount of phosphorus taken up by wheat plants and to set this in relation to the amount of available P predicted by different soil P extracting methods. The plant P uptake was in the magnitude of P extractable by the weakest extraction agents (H_2O, $CaCl_2$ and LiCl). An objective was also to identify extraction methods best representing the P uptake by plants over the course of one growing season. Results showed that weaker extracting agents, i.e. H_2O and $CaCl_2$ correlated best with the uptake by spring wheat over one growing season. This indicates that these weak extraction methods may be suitable indicators of plant-available P over one growing season. However, the potential resupply by the soil may not be assessed by these methods. The observed “over-extracting” of P by the stronger extracting agents may represent the amount that will become available in subsequent growing seasons. Thus, the stronger extracting agents (e.g. CAL, Mehlich 3, etc.) may provide information on the longer-term P buffering capacity of soils.

When grouping the soils according to their pH, their organic carbon content or their clay content, weaker extraction methods correlated better for soils with lower pH (and clay contents) while stronger extraction methods behaved contrary; they correlated better for soils with high pH (calcareous soils). Furthermore, stronger extraction methods showed a tendency to correlate better for soils of high organic carbon content. In conclusion, the results of this study suggest that a single method may not be sufficient to assess both current and potential plant available P.

Further insights could be gained by focusing on soils with very low P status. This could offer better information on the suitability of the extraction methods to predict the plant available P fraction. Similarly, it would be useful to utilize the very same pots for a long-term experiment involving several cropping cycles without P fertilization. When adding up the amounts of plant-extracted P it could hint to how well the studied soil extraction methods work for long-term prediction of P application necessity. As all plants have a very specific capacity to take up P *(HOLFORD, 1997)* varying plant species would be an interesting approach for further experiments. In regard to this, the occurrence of mycorrhizae, their role in the plant-soil system and the assessment by soil P extraction methods is largely unknown (*SCHACHTMAN et al., 1998)*. Certainly, further investigations on additional soil types would be interesting and as a concluding step, it would be necessary to apply the methods to field trials. Undoubtedly interesting is the exploration of new and innovative methods that may predict plant available P more accurately. *ZHANG et al. (1998)* have introduced the use of diffusive gradient in thin films (DGT) as a new method to determine the dissolved phosphorus in waters, and *Menzies et al. (2005)* applied the method to evaluate plant available phosphorus in soils. Recently, several experiments have proven the applicability of DGT to predict plant P uptake and response, and concluded that DGT is a very suitable method to predict fertilizer requirements *(Mason et al., 2010, Tandy et al., 2011)*.

5 References

ABDU, N. (2006) Soil- phosphorus extraction methodologies: A review. *African Journal of Agricultural Research* 1:159-161.

BISSANI, C. A., TEDESCO, M. J., CAMARGO, F. A. DE O., MIOLA, G. L. and GIANELLO, C. (2002) Anion-exchange resins and iron oxide-impregnated filter paper as plant available phosphorus indicators in soils. *Communications in Soil Science and Plant Analysis* 33: 1119-1130.

BLUME, H.-P., BRÜMMER, G. W., HORN, R., KANDELER, E., KÖGEL-KNABER, I., KRETZSCHMAR, R., STAHR, K. and WILKE, B.-M. (2010) Scheffer/Schachtschabel Lehrbuch der Bodenkunde. 16th Editon. Spektrum Akademischer Verlag, Heidelberg.

BLUM, W. E. H., SPIEGEL, H. and WENZEL, W. W. (1996) Bodenzustandsinventur - Konzeption, Durchführung und Bewertung. Empfehlung zur Vereinheitlichung der Vorgangsweise in Österreich, 2nd Edition. Bundesministerium f. Land- und Forstwirtschaft (Publisher), Wien.

BORTOLON, L. and GIANELLO, C. (2012) Multielement extraction from southern Brazilian soils. *Communications in Soil Science and Plant Analysis*, 43: 1615-1624.

BRAY, R. H. and KURTZ, L. T. (1945) Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59: 39-45.

CAMPBELL, A. S. and SCHWERTMANN, U. (1984) Iron oxide mineralogy of placic horizons. *Journal of Soil Science* 35: 569-582.

CHARDON, W. J. (2000) Methods of phosphorus analysis – phosphorus extraction with iron oxide-impregnated filter paper (Pi test) In: PIERZYNSKI, G. (Editor) Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. North Carolina State University. Raleigh, NC, USA: 27-30.

CLEVELAND, C. C. and LIPTZIN, D. (2007) C:N:P stoichiometry in soil: is there a “Redfield ratio” for the microbial biomass? *Biogeochemistry* 85: 235-252.

COHEN, Y. KIRCHMANN, H. and ENFÄLT, P. (2011) Management of phosphorus resources – Historical Perspective, Principal Problems and Sustainable Solutions. In: KUMAR, S. (Editor) Integrated Waste Management – vol. II. Intech Open Access Publisher : 247-268.

CONDRON, L. M. and TIESSEN, H. (2005) Interactions of organic phosphorus in terrestrial ecosystems. In: TURNER, B. L., FROSSARD, E. and BALDWIN, D. S. (Editors) Organic phosphorus in the environment. Wallington UK: CAB International: 295-307.

CORDELL, D., DRANGERT, J.-O. and WHITE, S. (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19: 292- 305.

CORDELL, D. and WHITE, S. (2011) Peak phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability* 3: 2027-2049.

CROSS, A. F. and SCHLESINGER, W. H. (1995) A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma* 64: 197-214.

CSATHÓ, P., MAGYAR, M., DEBRECZENI, K. and SÁRDI, K. (2005) Correlation between soil P and wheat shoot P contents in a network of hungarian long-term field trials. *Communications in Soil Science and Plant Analysis* 36: 275-293.

DIEPENBROCK, W., FISCHBECK, G., HEYLAND, K.-U., and KNAUER, N. (1999) Spezieller Pflanzenbau. 2nd Edition. Eugen Ulmer GmbH & Co, Stuttgart.

EFMA (2000) Phosphorus: Essential Element for Food Production. European Fertilizer Manufacturers Association (EFMA), Brussels. p. 9 Access: 13.02.2013 http://www.fertilizerseurope.com/site/index.php?id=387

EMSLEY, J. (2001) Phosphor - ein Element auf Leben und Tod. (Translated by Schleitzer Anna) Winley VCH, Weinheim.

FANGERIA, N. K. (2009) The Use of Nutrients in Crop Plants. CRC Press, Taylor and Francis Group, Boca Raton, CA.

FERNANDES, M. L., and COUNTINHO, J. (1997) Anion and cation exchange resin membranes to assess the phosphorus status of some Portuguese soils. *Communications in Soils Science and Plant Analysis* 28: 483-495.

FERNANDES, M. L. V., INDIATI, R., COUNTINHO, J. and BUONDONNO, A. (1999) Soil properties affecting phosphorus extraction from Portuguese soils by conventional and innovative methods. *Communications in Soils Science and Plant Analysis* 30: 921-936.

FRANK, K., BEEGLE D. and DENNING, J. (1998) Phosphorus. In: BROWN, J.R. (Editor) Recommended chemical soil test procedures for the north central region. North Central Regional Research Publication 221. Missouri Agricultural Experiment Station, Columbia, MO, USA: 21-30.

FROSSARD, E., JULIEN, P., NEYROUND, J.-A. and SINAJ, S. (2004) Phosphor in Böden – Standortbestimmung Schweiz, Schriftreihe Umwelt, 368. Bundesamt für Umwelt, Wald und Landschaft (Publisher), Bern.

HINSINGER, P., PLASSARD, C., TANG, C. and JAILLARD B. (2003) Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: A review. *Plant and Soil* 248: 43-59.

HOLFORD, I. C. R. (1997) Soil phosphorus: its measurement and its uptake by plants. *Australian Journal of Soil Research* 23: 417-427.

HOLMGREN, G.. (1967) A rapid citrate-dithionite extractable iron procedure. *Soil Science Society of America Proceedings* 31: 210-211.

HOUBA, V. J. G., TEMMINGHOFF, E. J. M., GAIKHORST, G. A. and VAN VARK, W. (2000) Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. *Communications in Soil Science and Plant Analysis* 31: 1299-1396.

HUSZ, G. (2001) Lithium chloride solution as an extracting agent for soils. *Journal of Plant Nutrition and Soil Science* 164: 71–75.

IFA (2012): Statistics: Production and Trade. International Fertilizer Industry Association (IFA). Access: 13.02.2013 http://www.fertilizer.org/ifa/HomePage/STATISTICS/Production-and-trade

JASINSKI, S. M. (2012) Phosphate Rock. U.S. Geological Survey, Mineral Commodity Summaries 2012: 118-119 Access: 14.11.2012 http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2012-phosp.pdf

JASINSKI, S. M. (2013) Phosphate Rock. U.S. Geological Survey, Mineral Commodity Summaries 2013: 118-119 Access: 13.02.2013 http://minerals.usgs.gov/minerals/pubs/mcs/2013/mcs2013.pdf

KULHÁNEK, M., BALÍK, J., ČERNÝ, J., NEDVĚD, V. and KOTKOVÁ, B. (2007) The influence of different intensities of phosphorus fertilising on available phosphorus contents in soil and uptake by plants. *Plant, Soil and Environment* 53: 382-387.

KULHÁNEK, M., BALÍK, J., ČERNÝ, J., SCHWEITZER, K., VANĚK, V. and PRÁŠILOVÁ, M. (2008) Evaluating of phosphorus quantity/intensity parameters in soil with different systems of organic fertilising. *Plant, Soil and Environment* 54: 389-394.

KULHÁNEK, M., BALÍK, J., ČERNÝ, J., KOZLOVSKÝ, O. and NEDVĚD, V. (2009a) The content of available phosphorus in soils and P uptake by plants. *Scientia Agriculturae Bohemica* 40: 105-109.

KULHÁNEK, M., BALÍK, J., ČERNÝ, J. and VANĚK, V. (2009b) Evaluating of phosphorus mobility in soil using different extraction methods. *Plant, Soil and Environment* 55: 267-272.

KUMAR, V., BOLLAND, M. D. A. and GILKES, R. J. (1994) Comparison of the Pi, Colwell, Bray 1, calcium acetate lactate (CAL) and Truog soil phosphorus test for predicting growth of oats, barley, triticale and clover in the field in lateritic soils fertilized with superphosphate and rock phosphate. *Fertilizer Research* 37: 115-124.

KUO, S. (1996). Chapter 32 Phosphorus. In: BARTELS, J. M. and BIGHAM, J. M. (Editors.) Methods of Soil Analysis 3. Chemical Methods. Soil Science Society of America, Madison, WI,USA: 869-919.

LAIR, G. J , ZEHETNER, F., HRACHOWITZ, M., FRANZ, N., MARINGER, F.-J. and GERZABEK, M. H. (2009) Dating of soil layers in a young floodplain using iron oxide crystallinity. *Quaternary Geochronology* 4: 260-266.

LIU, Y., VILLALBA, G., AYRES, R. U. and SCHRODER, H. (2008) Global phosphorus flows and environmental impacts from a consumption perspective. *Journal of Industrial Ecology* 12: 229-247.

MALLARINO, A. P. (2003) Field calibration for corn of the Mehlich-3 soil phosphorus test with colorimetric and inductively coupled plasma emission spectroscopy determination methods. *Soil Science Society of America Journal* 68: 1928-1934.

MAMO, T., RICHTER, C. and HEILIGTAG, B. (1996) Comparison of extractants for the determination of available phosphorus, potassium, calcium, magnesium and sodium in some Ethiopian and German soils. *Communications in Soil Science and Plant Analysis* 27: 2197-2212.

MARSCHNER, H. (1995) Mineral Nutrition of Higher Plants. Academic Press, San Diego, CA, USA. (3rd Edition).

MASON, S., MCNEILL, A., MCLAUGHLIN, M. J. and ZHANG, H. (2010) Prediction of wheat response to an application of phosphorus under field conditions using diffusive gradient in thin-films (DGT) and extraction methods. *Plant and Soil* 337: 243-258.

MEHLICH, A. (1978) New extractant for soil test evaluation of phosphorus, potassium, magnesium, calcium, sodium, manganese and zinc. *Communications in Soil Science and Plant Analysis* 9:477-492.

MEHRA, O. P. and JACKSON, M. L. (1960) Iron oxide removal from soils and clays by dithionite-cytrate systems buffered with sodium bicarbonate. Proceedings 7th national conference on *Clays and Clay minerals* 7: 317-322.

MENON, R. G., CHIEN, S. H. and HAMMOND, L. L. (1989a) Comparison of Bray I and Pi tests for evaluating plant-available phosphorus from soils treated with different partially acidulated phosphate rocks. *Plant and Soil* 114: 211-216.

MENON, R. G., CHIEN, S. H. HAMMOND, L. L. and HENAO, J. (1989b) Modified techniques for preparing paper strips for the new Pi soil test for phosphorus. *Fertilizer Research* 19: 85-91.

MENON, R. G., CHIEN, S. H. and NABI GADALLA, A. EL. (1991) Comparison of Olsen and Pi soil tests for evaluating phosphorus bioavailability in a calcareous soil treated with single superphosphate and partially acidulated phosphate rock. *Fertilizer Research* 29: 153-158.

MENON, R. G., HAMMOND, L. L. and SISSINGH, H. A. (1988) Determination of plant-available phosphorus by the iron hydroxide-impregnated filter paper (P_i) Soil Test. *Soil Science Society of America Journal* 52: 110-115.

MENZIES, N. W., KUSUMO, B. and MOODY, P. W. (2005) Assessment of P availability in heavily fertilized soils using the diffusive gradient in thin films (DGT) technique. *Plant and Soil* 269: 1–9.

MING, D. W. (2006) Carbonates. Encyclopedia of Soil Science. Taylor & Francis: 202-205.

MORTVEDT, J. J. AND BEATON, J. D. (1995) Heavy metal and radionuclide contaminants in phosphate fertilizers. In: TIESSEN, H. (Editor) Phosphorus in the Global Environment: Transfer, Cycles and Management. John Wiley and Sons, New York: 93-106.

MURPHY, J. and RILEY, J. P. (1962) A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27: 31-36.

MYERS R. G., SHARPLEY A. N., THIEN S. J. and PIERZYNSKI G. M. (2005). Ion-Sink phosphorus extraction methods applied on 24 soils from the continental USA. *Soil Science Society of America Journal* 69: 511-521.

OBERSON, A. and JONER, E. J. (2005) Microbial turnover of phosphorus. In: TURNER, B. L., FROSSARD, E. and BALDWIN, D. S. (Editors) Organic Phosphorus in the Environment. CAB International, Wallingford, Oxon, UK: 133-164.

NUERNBERG, N. J., LEAL, J. E. AND SUMNER, M. E. (1998) Evaluation of an anion-exchange membrane for extracting plant available phosphorus in soils. *Communications in Soil Science and Plant Analysis* 29: 467-479

O'HALLORAN, I. P., STEWART, J. W. B. and KACHANOSKI, R. G. (1987) Influence of texture and management practices on the forms and distribution of soil phosphorus. *Canadian Journal of Soil Science* 67: 147-163.

OLSEN, S. R., COLE, C. V., WATANABE, F. S. and DEAN, L. A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circular 939*. Washington D. C.: U. S. Government Printing Office: 1-19.

OLSEN, S. R. and SOMMERS, L. E. (1982) Phosphorus. In: PAGE, A. L., MILLER R. H. and KEENEY D. R. (Editors) Methods of soil analysis, part 2. Chemical and Microbiological Properties. Agronomy Monograph 9. 2nd Edition, American Society of Agronomy and Soil Science Society of America, Madison, WI: 403-430.

OENORM L 1061-1 (2002) Physical analysis of soils - Determination of particle size distribution in mineral soils - Part 1: Coarse soil

OENORM L 1061-2 (2002) Physical analysis of soils - Determination of particle size distribution in mineral soils - Part 2: Fine soil

OENORM L 1080 (1999) Chemical analyses of soils - Determination of organic carbon by dry combustion with and without consideration of carbonates.

OENORM L 1084 (2006) Chemical analyses of soils – Determination of carbonate.

OENORM L 1087 (2006) Chemical analysis of soils — Determination of "plant-available" phosphorus and potassium by the calcium-acetate-lactate (CAL)-method.

OENORM L 1092 (2005) Chemical analysis of soils - Extraction of water soluble elements and compounds.

OENORM L 1201 (2007) Chemical analyses of soils - Extraction for the determination of oxalate soluble iron, aluminium and manganese.

OENORM S 2122-1 (2004) Soils from waste - Part 1: Fractional analysis - Methods of analysis.

PARDO, P., LÓPEZ-SÁNCHEZ, J. F. and RAURET, G. (2003) Relationship between phosphorus fractionation and major components in sediments using the SMT harmonised extraction procedure. *Analytical and Bioanalytical Chemistry* 376: 248-254.

PIERZYNSKI, G. M., SHARPLEY, A. N. and KOVAR, J. L. (2009) Introduction. In: PIERZYNSKI, G. M. and KOVAR, J. L. (Editors) Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. 2nd Edition. Southern Cooperative Series Bulletin, 408. North Carolina State University. Raleigh, NC, USA: 1-4.

PIERZYNSKI, G. M., ZHANG, H., WOLF, A., KLEINMAN, P., MALLARINO, A. and SULLIVAN, D. (2011) Phosphorus Determination in Waters and Extracts of Soils and By-Products: Inductively Coupled Plasma Spectrometry versus Colorimetric Procedures. Access: 14.11.2012 http://www.sera17.ext.vt.edu/Documents/P_Analysis_ Comparisons.pdf

RAISWELL, R., CANFIELD., D. E. and BERNER, R. A. (1994) A comparison of iron extraction methods for the determination of degree of pyritization and recognition of iron-limited pyrite formation. *Chemical Geology*, 111: 101-111.

RECHBERGER, H., EGLE, L. and ZESSNER, M. (2013) Ressource Phosphor: Verfügbarkeit, Nutzung, Optimierung. *Wiener Mitteilungen* 228: 105-120.

RÖMER, W. (2006) Vergleichende Untersuchungen zur Pflanzenverfügbarkeit von Phosphat aus verschiedenen P-Recycling-Produkten im Keimpflanzenversuch. *Journal of Plant Nutrition and Soil Science* 169: 826-832.

RUTTENBERG, K.C. (2009) The global phosphorus cycle. *Treatise on Geochemistry* 9: 585-591.

RYAN, J. and RASHID, A. (2006) Phosphorus. Encyclopedia of Soil Science. Taylor & Francis: 1275-1283.

SAGGAR, S., HEDLEY, M. J. and WHITE, R. E. (1999) Development and evaluation of an improved soil test for phosphorus, 3: field comparison of Olsen, Colwell and resin soil P tests for New Zealand pasture soils. *Nutrient Cycling in Agroecosystems* 55: 35-50.

SCHACHTMAN, D. P., REID, R. J. and AYLING S. M. (1998) Phosphorus uptake by plants: From soil to cell. *Plant Physiology* 116: 447-453.

SCHLESINGER, W. H. (1997) Biogeochemistry: An Analysis of Global Change. 2nd Edition. Academic Press. San Diego, CA: 383-401.

SCHNUG, E. (2012) Uran in Phosphor-Düngemitteln und dessen Verbleib in der Umwelt. *Strahlentelex* 612-613: 3-10.

SCHOENAU, J. J. and O'HALLORAN, I. P. (2007) Chapter 8 sodium bicarbonate-extractable phosphorus. In: CARTER, M.R. and GREGORICH, E.G. (Editors) Soil Sampling and Methods of Analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL, USA: 89-94.

SCHÜLLER, H. (1969) Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphors im Boden. *Zeitschrift für Pflanzenernährung und Bodenkunde* 123: 48-63.

SEELING, B. and JUNGK, A. (1996) Utilization of organic phosphorus in calcium chloride extracts of soil by barley plants and hydrolysis by acid and alkaline phosphatases. *Plant and Soil* 178: 179-184.

SLAFER, G. A. (2007) Physiology of determination of major wheat yield components. In: BUCK, H. T., NISI, J. E. and SALOMÓN, N. (Editors) Wheat Production in Stressed Environments. Springer, Mar del Plata, Argentina: 557-565.

SIMS, J. T. (2000) Soil test phosphorus: Mehlich 3. In: PIERZYNSKI, G. (Editor) Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. North Carolina State University. Raleigh, NC, USA: 17-19.

SIMS, J. T. (2000) Soil test phosphorus: Olsen P. In: PIERZYNSKI, G. (Editor) Methods of Phosphorus Analysis for Soils, Sediments, Residuals, and Waters. North Carolina State University. Raleigh, NC, USA: 20-21.

SMIL, V. (2000) Phosphorus in the environment: natural flows and human interferences. *Annual Review of Energy and the Environment* 25: 53-88.

SMIT, A. L. (2011) Phosphorus depletion: An invisible crisis? Access: 13.02.2013 http://knowledge.cta.int/Dossiers/S-T-Issues/Phosphorus-depletion/Feature-articles/Phosphorus-depletion-an-invisible-crisis

STEFFENS, D., LEPPIN, T., LUSCHIN-EBENGREUTH, N., YANG, Z. M. and SCHUBERT, S. (2010) Organic soil phosphorus considerably contributes to plant nutrition but is neglected by routine soil-testing methods. *Journal of Plant Nutrition and Soil Science* 173: 765-771.

TANDY, S., MUNDUS, S., YNGVESSON, J., DE BANG, T. C, LOMBI, E., SCHJOERRING, J. K. and HUSTED, S. (2011) The use of DGT for prediction of plant available copper, zinc and phosphorus in agricultural soils. *Plant and Soil* 346: 167-180.

TIESSEN, H. (2008) Phosphorus in the global environment. In: WHITE, P. J. and HAMMOND J. P. (Editors) The Ecophysiology of Plant-Phosphorus Interactions. Springer Science + Business Media B.V Dordrecht: Springer, Dordrecht: 1-7.

TIESSEN, H. and MOIR J. O. (1993) Characterization of available P by sequential extraction. In: CARTER M.R. (editor): Soil Sampling and Methods of Analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL, USA: 75–86.

TORRENT, J., SCHWERTMANN, U. and SCHULZE, D. G. (1980) Iron oxide mineralogy of some soils of two river terrace sequences in Spain. *Geoderma* 23: 191-208.

TUNESI, S., POGGI, V. and GESSA, C. (1999) Phosphate adsorption and precipitation in calcareous soils: the role of calcium ions in solution and carbonate minerals. *Nutrient Cycling in Agroecosystems* 53: 219 - 227.

VAN RAIJ, B. (1998) Bioavailable tests: Alternatives to standard soil extractions. *Communications in Soil Science and Plant Analysis* 29: 1553-1570.

ZBÍRAL, J. and NĚMEC, P. (2002) Comparison of Mehlich 2, Mehlich 3, CAL, Egner, Olsen, and 0.01 M $CaCl_2$ extractants for determination of phosphorus in soils. *Communications in Soil Science and Plant Analysis* 33: 3405-3417.

ZBÍRAL, J. (2000) Determination of phosphorus in calcareous soils by Mehlich 3, Mehlich 2, CAL, and Egner extractants for determination of phosphorus in soils. *Communications in Soil Science and Plant Analysis* 31: 3037-3048.

ZEHETNER, F., LAIR, G. J., MARINGER, F.-J., GERZABEK, M. H. and HEIN, T. (2008) From sediment to soil: floodplain phosphorus transformations at the Danube river. *Biogeochemistry* 88: 117-126.

ZHENG, Z. M. and ZHANG T. Q. (2012) Soil Phosphorus Tests and Transformation Analysis to Quantify Plant Availability: A Review. In: WHALEN, J. (Editor) Soil Fertility Improvement and Integrated Nutrient Management – A Global Perspective. InTech (Publisher): 19-36 Access: 10.02.1013 http://cdn.intechopen.com/pdfs/26943/InTech-Soil_phosphorus_tests_and_transformation_analysis_to_quantify_plant_availability_a_review.pdf

ZHANG H., DAVISON W., GADI R. and KOBAYASHI T. (1998) In situ measurement of dissolved phosphorus in natural waters using DGT. *Analytica Chimica Acta* 370: 29-38.

ZIADI, N. and SEN TRAN, T. (2007) Chapter 7 Mehlich 3-Extractable Elements. In: CARTER, M.R. and GREGORICH, E.G. (Editors) Soil Sampling and Methods of Analysis. Canadian Society of Soil Science, Lewis Publishers, Boca Raton, FL, USA: 81-88.

ZORN, W. and KRAUSE, O. (1999) Untersuchungen zur Charakterisierung des pflanzenverfügbaren Phosphats in Thüringer Carbonatböden. *Journal of Plant Nutrition and Soil Science* 162: 463-469.

6 Appendix

All the data used for this study is given in the appendix. The Curriculum vitae can be found on the last page of the appendix.

Table 15: Raw data of soil characteristics and physicochemical properties

Sample No.	pH (H_2O)	pH (KCl)	[a] EC	[b] OC	$CaCO_3$	C/N (molar)	C/P (molar)	N/P (molar)	[c] KH	Clay	Silt	Sand
			[mS cm^{-1}]	[%]					[mL 100 g^{-1}]	[%]		
P3	7.5	7.0	0.64	2.03	13.0	10.2	116	11.4	52.4	26.7	25.8	46.3
P4	7.5	6.8	0.56	2.02	6.1	11.6	112	9.7	56.1	30.0	25.3	44.0
P5	7.6	6.8	0.83	1.71	1.1	11.0	139	12.6	62.7	24.9	45.1	29.1
P6	7.6	6.3	0.56	1.45	0	11.4	104	9.1	63.5	24.2	41.5	33.5
P9	7.1	6.0	0.66	1.49	0	12.4	111	8.9	56.8	24.9	45.6	29.3
P10	7.0	6.1	0.88	0.93	0	13.7	125	9.1	33.6	15.5	34.9	48.9
P15	7.8	6.8	0.73	2.36	24.9	11.2	129	11.5	117.2	37.5	47.4	14.3
P17	7.8	7.1	0.70	3.86	56.2	10.6	358	33.6	53.1	34.3	39.4	25.5
P18	7.9	6.9	0.68	4.03	27.0	11.2	273	24.4	121.2	38.9	46.8	13.7
P19	7.9	7.1	0.56	1.90	26.9	11.5	145	12.6	65.8	25.8	58.7	14.4
P20	7.9	7.1	0.63	1.92	26.8	11.3	153	13.5	68.5	25.8	58.8	14.8
P22	7.7	7.0	0.62	2.06	26.8	10.8	185	17.2	67.7	25.2	60.6	13.3
P23	7.8	7.0	0.48	2.06	18.6	12.5	120	9.6	70.4	28.1	53.6	18.3
P26	7.9	7.0	0.40	1.94	19.9	12.6	117	9.3	65.6	29.0	52.4	18.5
P28	7.9	7.1	0.69	2.02	15.5	12.8	126	9.9	59.4	30.8	47.4	20.1
P29	8.0	6.6	0.33	1.15	0.04	11.7	95	8.2	54.6	25.7	60.4	13.1
P30	7.7	6.4	0.47	1.15	0	9.7	95	9.8	49.4	25.5	60.8	13.1
P31	7.5	6.2	0.43	1.44	0	12.6	116	9.2	47.4	26.4	59.3	13.4
P32	7.5	6.1	0.37	1.15	0	11.3	141	12.5	55.7	26.7	60.0	12.9
P33	7.5	5.7	0.36	1.03	0	11.7	111	9.5	48.8	23.2	49.6	26.5
P34	7.5	5.5	0.34	1.02	0	10.9	108	9.9	45.1	23.1	48.9	27.8
P35	7.4	5.4	0.23	1.02	0	11.4	86	7.5	45.4	23.8	48.8	26.7
P36	7.3	5.4	0.32	0.97	0	9.5	90	9.5	48.5	23.2	49.4	27.0
P41	7.2	5.4	0.49	1.74	0	10.7	85	7.9	75.4	30.5	38.0	30.8
P43	7.2	5.5	0.69	1.89	0	11.7	98	8.3	77.9	23.5	54.2	21.8
P44	6.9	4.6	0.43	1.32	0	11.7	89	7.6	65.1	24.5	45.6	29.5
P49	6.7	4.5	0.46	1.37	0	15.7	84	5.4	35.2	13.2	22.9	63.8
P50	6.7	4.3	0.39	1.44	0	15.6	124	8.0	36.3	12.2	22.1	65.3
P51	6.6	6.0	0.52	1.44	0	14.1	99	7.0	38.1	14.0	23.1	62.6
P52	6.5	4.7	0.41	1.50	0	14.2	116	8.2	38.7	11.5	22.6	65.5
P57	6.3	5.1	0.45	0.97	0	14.5	222	15.3	26.6	15.9	19.1	64.3
P58	6.4	5.3	0.67	1.30	0	17.8	226	12.7	31.4	15.6	17.9	65.5
P59	6.3	4.9	1.12	1.09	0	20.2	198	9.8	29.1	15.7	18.4	65.1
P60	6.3	5.5	0.38	0.97	0	15.7	186	11.8	26.0	14.6	18.5	66.0
P61	6.1	5.1	1.32	1.11	0	15.4	208	13.5	30.1	14.5	19.6	65.2
P63	7.1	6.5	0.77	1.87	0	10.5	130	12.4	51.9	27.9	48.3	22.5
P65	7.2	6.2	1.26	1.45	0	18.0	237	13.2	32.0	4.2	9.1	86.2
P66	7.5	6.7	0.82	2.83	1.2	13.6	329	24.1	41.5	5.9	18.2	75.6
P67	7.0	5.6	1.35	2.67	0	25.1	520	20.7	39.3	5.6	12.9	80.9
P68	6.6	4.8	1.06	1.38	0	19.6	291	14.8	31.7	8.1	14.4	77.1
P69	6.9	5.8	1.01	1.32	0	13.7	301	21.9	39.8	12.5	17.6	68.8
P70	7.0	5.5	0.89	1.95	0	11.7	163	13.9	88.2	43.2	54.5	1.5
P71	7.0	5.7	0.58	0.98	0	15.4	120	7.8	37.9	12.1	48.2	39.7
P72	6.9	5.9	0.89	3.81	0	13.9	215	15.5	64.4	15.7	20.8	63.0
P73	7.1	5.8	0.64	2.67	0	9.9	253	25.6	118.6	53.2	32.2	14.7
P74	7.0	5.2	0.42	1.15	0	10.5	145	13.8	52.3	18.8	58.4	21.9
P75	6.8	5.4	0.59	2.19	0	10.4	79	7.6	59.0	25.3	49.4	25.0
P76	7.7	6.8	0.60	1.62	16.8	13.1	192	14.6	79.2	35.5	59.8	4.2
P77	7.8	6.5	0.91	1.19	0	9.0	564	63.0	43.8	15.1	56.2	28.4
P78	7.7	6.4	0.93	1.94	0	12.8	244	19.1	58.1	30.5	63.6	5.0

[a] EC = electrical conductivity in saturated H_2O extract

[b] OC = organic carbon

[c] KH = amount of water necessary to prepare the H_2O saturation extract

Sample No.	[d] CEC$_{pot}$	[e] BS	Ca	Mg	K	Al	[f] Fe$_d$	[f] Mn$_d$	[g] Fe$_o$	[g] Mn$_o$	[fg] Fe$_o$/Fe$_d$	[g] P$_o$/Fe$_o$ (molar)
	[cmol$_c$ kg^{-1}]	[% CEC$_{pot}$]					[mg kg^{-1}]					
P3	13.7	94	81.7	10.1	1.2	0.6	6902	605	2280	471	0.33	0.61
P4	15.5	91	79.3	9.9	0.8	0.4	8379	681	2568	596	0.31	0.44
P5	12.0	89	67.7	13.6	6.9	3.5	8208	631	4506	576	0.55	0.31
P6	12.9	66	48.8	13.8	3.1	1.9	8329	613	3809	478	0.46	0.23
P9	11.2	60	41.6	9.9	7.4	2.0	13357	992	3901	785	0.29	0.28
P10	7.4	62	46.5	8.4	5.7	3.4	9338	495	2177	455	0.23	0.31
P15	18.0	90	75.3	8.5	5.1	0.4	9336	350	1261	87	0.14	0.72
P17	14.2	97	80.9	13.1	2.1	1.6	1863	67	930	71	0.5	0.74
P18	27.1	92	76.1	14.9	0.5	0.3	10785	446	2405	286	0.22	0.29
P19	11.7	96	81.2	11.9	2.3	1.2	8404	447	2742	53	0.33	0.27
P20	11.5	97	80.9	12.5	2.7	1.2	8320	437	2724	47	0.33	0.27
P22	12.2	95	80.2	11.9	2.6	1.3	8450	435	2771	47	0.33	0.28
P23	13.9	95	82.2	10.4	2.1	0.3	7339	470	1443	203	0.2	0.66
P26	13.8	94	82.6	9.7	1.5	0.3	7099	450	1381	181	0.19	0.65
P28	12.5	96	79.3	13.0	3.0	0.4	5476	322	1128	252	0.21	0.84
P29	10.6	85	72.0	9.6	3.1	2.2	9690	663	4876	516	0.5	0.16
P30	12.4	68	57.1	7.8	2.3	0.7	9313	661	5002	508	0.54	0.16
P31	12.1	68	58.0	7.8	2.2	0.7	9495	624	5046	509	0.53	0.16
P32	12.7	68	58.2	7.5	2.2	0.6	9673	614	5124	575	0.53	0.19
P33	11.1	63	51.0	8.1	3.2	0.7	9887	510	5629	411	0.57	0.2
P34	16.1	43	35.5	5.1	2.0	0.4	10180	499	5462	388	0.54	0.16
P35	12.9	54	45.0	6.1	2.6	0.5	10662	766	5514	418	0.52	0.18
P36	11.6	60	50.7	6.6	2.5	0.8	10827	533	5460	397	0.5	0.24
P41	17.0	60	49.2	8.5	1.7	1.1	22610	885	7132	733	0.32	0.1
P43	15.3	59	47.7	10.0	1.0	1.4	17781	583	5438	441	0.31	0.19
P44	14.1	56	44.6	6.8	3.9	1.2	17819	546	5004	468	0.28	0.21
P49	10.7	26	18.5	4.0	2.7	1.2	7731	412	3698	379	0.48	0.36
P50	11.6	21	14.7	3.0	3.2	1.0	7759	392	3451	338	0.44	0.29
P51	9.6	44	31.9	8.6	3.0	1.7	8477	415	3627	338	0.43	0.29
P52	12.6	25	18.2	3.6	2.3	1.5	8031	407	6446	623	0.8	0.36
P57	7.6	71	64.4	5.0	0.6	3.6	6791	265	2695	262	0.4	0.12
P58	13.0	42	35.7	4.8	1.3	7.1	6932	293	2621	237	0.38	0.24
P59	11.2	41	34.3	4.4	2.0	5.8	6802	293	2707	251	0.4	0.2
P60	13.0	40	33.2	3.7	2.3	3.4	7381	387	3107	312	0.42	0.23
P61	9.0	53	45.3	4.6	1.9	5.8	7342	383	3105	326	0.42	0.21
P63	12.8	70	59.9	4.1	5.8	4.4	12125	689	4745	519	0.39	0.2
P65	7.4	65	56.1	4.5	3.6	2.6	2565	234	1222	169	0.48	0.84
P66	11.8	87	79.1	3.7	4.2	3.6	7886	276	4770	244	0.6	0.28
P67	9.3	49	41.2	4.8	2.2	1.1	n.d.	n.d.	1693	150	n.d.	0.78
P68	6.2	38	25.9	4.8	6.9	2.1	3058	170	1778	153	0.58	0.44
P69	7.4	76	59.7	8.6	6.3	6.8	3178	273	1251	163	0.39	0.3
P70	20.0	64	52.7	6.4	4.0	4.8	12004	830	3550	769	0.3	0.18
P71	6.9	56	42.2	10.9	1.6	2.7	4737	566	2238	483	0.47	0.26
P72	18.4	61	44.1	15.8	0.8	2.7	42990	334	21949	265	0.51	0.08
P73	29.1	71	62.0	6.8	0.6	0.2	12565	480	10350	383	0.82	0.18
P74	10.7	53	46.7	3.9	1.7	3.3	8646	449	4097	482	0.47	0.14
P75	20.7	40	28.1	8.8	2.7	0.8	24285	1010	10856	821	0.45	0.17
P76	13.6	89	77.6	7.7	2.7	1.5	7108	292	2682	267	0.38	0.19
P77	7.3	83	72.5	6.4	3.8	11.4	4951	387	2417	356	0.49	0.24
P78	14.5	76	65.9	7.1	2.9	5.4	6304	481	1651	439	0.26	0.25

[d] CEC$_{pot}$ = potential cation exchange capacity (determined at pH 8.1)

[e] BS = base saturation

[f] Fe$_d$ and Mn$_d$ = dithionite-extractable Fe and Mn

[g] Fe$_o$, Mn$_o$ and P$_o$ = oxalate-extractable Fe, Mn and P

Table 16: Raw data of the applied soil P extraction methods

Sample No.	H_2O	$CaCl_2$	LiCl	Fe-oxide P_i	Olsen	CAL	AEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate	Total P
	[mg kg^{-1}]													
P3	0.39	3.80	12.7	53.7	62.9	237.9	100.7	200.0	408.8	187.9	451	427	769	1210
P4	0.12	1.52	5.05	27.1	36.2	178.0	71.7	132.6	292.7	150.6	465	326	625	1049
P5	1.43	5.62	34.8	79.5	100.0	267.1	246.2	310.2	409.8	261.6	317	567	783	1144
P6	0.47	1.35	12.6	49.1	38.7	75.1	125.5	103.8	164.0	165.7	361	272	476	831
P9	1.79	9.62	23.4	103.9	76.6	149.5	194.5	207.7	245.2	243.8	347	315	596	906
P10	0.30	4.46	10.1	48.9	47.3	101.9	110.3	153.4	190.9	172.8	192	235	378	602
P15	0.10	0.76	3.21	17.2	22.8	64.8	35.4	53.6	73.4	87.0	473	224	504	926
P17	0.03	0.91	2.72	20.0	36.1	89.0	52.2	46.6	3.1	88.8	278	303	380	800
P18	0.09	0.57	1.25	16.4	24.8	35.1	41.9	40.0	38.5	91.6	381	186	382	817
P19	0.08	1.07	4.00	18.5	27.5	72.1	37.7	74.9	79.0	98.7	338	268	410	874
P20	0.09	1.39	5.31	21.5	34.7	77.6	44.6	83.1	140.8	104.2	324	293	408	894
P22	0.11	1.04	4.59	20.4	32.1	78.7	40.4	80.2	96.0	101.7	287	305	424	877
P23	0.10	0.76	2.33	16.3	21.6	70.1	31.1	57.0	81.7	69.4	441	241	529	892
P26	0.07	0.37	1.67	13.3	16.2	54.4	23.8	41.8	59.3	61.2	426	206	496	811
P28	0.08	0.10	4.19	20.8	27.0	76.2	45.1	71.1	85.3	70.0	412	252	525	849
P29	0.06	0.76	1.52	28.3	28.8	44.4	88.5	55.8	95.8	170.9	312	290	423	768
P30	0.06	1.08	1.65	34.0	31.8	46.6	90.2	64.7	140.5	195.6	312	308	440	791
P31	0.08	1.23	2.34	37.3	37.5	57.1	109.9	78.3	191.3	210.8	321	293	458	849
P32	0.27	2.32	6.37	65.2	53.6	86.6	148.7	115.4	244.2	246.9	210	360	549	920
P33	0.18	2.62	5.02	58.6	58.3	101.1	117.2	119.6	159.9	284.4	239	460	634	957
P34	0.07	1.30	2.26	32.1	40.6	64.7	82.6	77.2	122.3	253.4	244	381	480	846
P35	0.11	2.07	2.99	48.0	48.6	81.5	93.7	94.9	143.7	281.9	307	438	552	926
P36	0.29	3.68	5.96	67.4	73.5	149.3	138.9	154.5	206.4	369.1	277	554	715	1098
P41	0.11	0.95	2.75	38.3	34.4	49.5	73.1	55.1	79.1	270.9	529	129	410	843
P43	0.19	1.48	5.53	34.7	35.7	57.8	102.3	78.5	100.1	217.5	500	381	582	1198
P44	0.56	5.78	8.54	57.6	65.1	94.0	121.9	170.9	195.8	218.8	385	368	596	966
P49	0.11	2.54	4.18	66.6	80.3	117.6	120.6	288.2	300.9	409.9	419	313	737	978

Sample No.	H_2O	$CaCl_2$	LiCl	Fe-oxide P_i	Olsen	CAL	AEM	Mehlich 3	Bray II	Dithionite	Organic P	HCl	Oxalate	Total P
							[mg kg^{-1}]							
P50	0.04	0.85	1.94	35.2	51.6	70.6	73.3	176.7	203.5	337.0	300	230	564	694
P51	0.08	1.20	2.97	41.9	50.2	74.5	86.8	177.9	214.2	315.6	375	250	592	820
P52	0.46	4.73	8.61	102.9	108.6	166.2	158.1	390.8	467.2	424.1	334	364	1296	1075
P57	0.03	0.38	b.d.	21.6	13.7	17.8	30.6	32.6	46.8	78.7	113	168	179	298
P58	0.24	3.53	6.87	52.2	39.2	63.4	104.0	151.4	176.6	160.5	148	201	347	510
P59	0.17	3.53	6.33	49.4	42.2	57.1	77.1	122.4	138.0	127.0	142	159	295	436
P60	0.59	6.46	12.12	93.4	71.7	152.2	165.7	252.0	295.8	185.4	135	338	401	645
P61	0.28	4.83	9.09	74.5	55.2	91.6	123.1	214.2	264.0	n. d.	137	333	365	599
P63	0.22	2.29	10.8	48.7	75.8	181.6	154.2	188.1	211.9	360.8	371	476	538	1021
P65	0.22	5.57	18.3	92.1	83.9	181.8	149.4	406.2	456.6	n. d.	158	376	570	688
P66	0.15	2.59	10.3	40.7	79.5	259.1	94.6	200.3	340.1	303.8	222	622	731	983
P67	0.30	6.43	12.8	122.1	117.0	241.7	179.6	540.0	628.0	157.2	132	462	729	728
P68	1.07	10.5	16.8	72.3	70.4	112.1	193.7	233.8	252.0	191.9	122	254	430	476
P69	0.12	2.81	4.93	30.5	25.3	41.3	50.4	63.8	94.7	81.8	113	139	210	310
P70	0.14	0.95	3.29	23.0	32.8	38.9	62.3	48.6	80.0	122.6	308	149	358	579
P71	0.04	1.51	2.79	24.4	20.8	35.4	47.8	76.1	94.4	145.2	211	138	326	441
P72	0.09	1.15	4.14	46.5	58.6	66.8	119.7	62.2	88.1	515.4	458	523	1008	1347
P73	0.82	3.09	9.29	85.4	123.6	178.4	228.2	156.9	155.3	414.1	272	594	1042	1204
P74	0.04	0.78	1.34	19.0	23.6	35.5	40.4	53.4	67.8	145.2	205	131	323	450
P75	0.18	2.03	4.97	60.3	69.6	90.7	181.8	166.1	201.1	606.8	716	386	1040	1677
P76	0.03	0.42	1.54	5.6	10.8	46.7	20.5	27.2	37.5	44.4	217	271	288	654
P77	0.25	3.07	10.4	54.5	42.5	142.8	187.6	192.6	213.0	157.8	54.4	313	325	548
P78	0.05	1.06	2.83	18.4	21.7	40.5	58.2	45.9	98.9	64.3	205	173	233	444

Table 17: Raw data of plant analysis

Sample No.	[a] DM grain yield	[a] DM straw yield	Ears per m^2	Grains per ear	Thousand-seed weight	P content grain	P content straw	Total P uptake
	[g m^{-2}]				[g]	[mg kg^{-1}]		[mg m^{-2}]
P3	152.8	229.0	283	14	43.9	4520	969	911
P4	156.6	307.6	433	9	45.1	4910	935	1056
P5	154.7	257.1	358	15	32.5	4190	1089	927
P6	162.3	237.7	301	17	37.9	4200	1056	932
P9	128.3	285.3	283	17	31.6	4220	2815	1343
P10	158.5	205.9	283	19	34.3	5140	763	971
P15	156.6	191.9	283	17	36.8	4360	540	786
P17	126.4	164.1	283	16	33.4	4520	448	643
P18	188.7	239.6	283	20	37.9	4010	817	951
P19	162.3	183.3	283	18	36.9	3860	520	720
P20	143.4	179.1	283	17	34.4	3230	728	593
P22	171.7	168.4	283	20	34.6	4460	530	853
P23	126.4	164.1	283	16	32.3	3890	517	576
P26	122.6	152.4	283	17	30.1	4510	450	621
P28	150.9	190.4	301	16	36.8	4210	445	718
P29	169.8	183.5	283	18	38.1	4680	338	855
P30	177.4	193.6	283	18	39.9	4330	471	857
P31	171.7	199.5	283	18	39.5	4450	591	880
P32	183.0	220.2	320	17	39.4	4560	590	963
P33	171.7	201.0	283	18	39.9	4240	715	871
P34	177.4	204.9	283	19	39.0	3780	723	817
P35	149.1	206.2	283	17	37.0	4330	864	823
P36	167.9	211.5	301	18	37.0	3760	549	746
P41	173.6	262.2	320	17	36.1	4480	658	949
P43	181.1	302.9	301	20	35.2	3890	622	892
P44	186.8	273.7	301	19	37.5	4130	990	1042
P49	132.1	186.1	283	17	32.4	3300	533	534
P50	117.0	164.2	264	17	30.2	3430	390	465
P51	154.7	224.3	283	19	32.7	4120	564	764
P52	169.8	206.6	264	21	35.5	3990	669	814
P57	101.9	155.8	283	15	28.4	4180	934	571
P58	122.6	165.0	301	13	37.2	3960	746	607
P59	141.5	226.8	320	14	37.8	4200	841	785
P60	122.6	167.8	301	14	33.7	5380	1418	896
P61	143.4	230.0	283	16	36.7	4270	1207	889
P63	164.2	208.9	283	18	36.9	2970	494	590
P65	160.4	318.9	414	14	31.5	2950	899	759
P66	183.0	220.6	301	20	36.2	3870	481	814
P67	203.8	295.0	320	18	40.3	3810	762	1000
P68	177.4	300.8	358	17	34.7	5270	1554	1400
P69	183.0	234.1	320	18	37.5	4430	922	1025
P70	158.5	293.8	301	16	37.4	4390	884	954
P71	158.5	191.2	283	18	36.6	4020	730	776
P72	169.8	277.1	301	18	35.6	4390	850	979
P73	186.8	269.3	358	17	35.4	4220	783	998
P74	162.3	225.1	283	18	37.2	4960	892	1003
P75	179.3	246.5	377	19	29.7	5060	806	1105
P76	122.6	160.3	283	16	31.0	3330	340	462
P77	149.1	194.6	264	17	38.0	4020	1212	834
P78	135.9	197.4	283	16	35.9	3970	839	704

[a] DM = dry matter

Table 18: Transfer factors from different soil P pools to wheat grain (tfG) correlated with soil parameters, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	pH (H_2O)	pH (KCl)	[a] EC	[b] OC	$CaCO_3$	C/N (molar)	C/P (molar)	N/P (molar)	[c] KH	Clay	Silt	Sand
tfG H_2O	0.161	0.119	-0.281 *	0.09	0.347 *	-0.121	-0.012	0.042	-0.015	0.118	0.245	-0.220
tfG $CaCl_2$	0.297 *	0.296 *	-0.114	0.137	0.274	-0.101	-0.106	-0.064	0.164	0.256	0.194	-0.247
tfG LiCl	0.346 *	0.155	-0.416 **	0.116	0.252	-0.272	-0.197	-0.086	0.288 *	0.315	0.462 ***	-0.453 ***
[d] **tfG Fe-oxide P_i**	0.437 **	0.449 **	-0.160	0.206	0.542 ***	-0.212	-0.036	0.044	0.404 **	0.431 **	0.444 **	-0.490 ***
tfG Olsen	0.268	0.296 *	-0.193	-0.026	0.331 *	-0.148	-0.056	0.006	0.215	0.282 *	0.362 **	-0.371 **
[e] **tfG CAL**	-0.09	-0.110	-0.172	-0.11	-0.003	-0.058	-0.074	-0.059	0.063	0.117	0.189	-0.182
[f] **tfG AEM**	0.339 *	0.390 **	-0.192	0.148	0.564 ***	-0.145	-0.069	-0.021	0.308 *	0.311 *	0.320 *	-0.353 *
tfG Mehlich 3	0.341 *	0.303 *	-0.211	0.236	0.416 **	-0.284 *	-0.039	0.059	0.403 **	0.470 ***	0.421 **	-0.491 ***
tfG Bray II	0.187	0.227	0.007	0.444 **	0.669 ***	-0.133	0.252	0.321 *	0.043	0.216	0.034	-0.115
tfG Dithionite	0.375 **	0.483 ***	0.157	0.147	0.557 ***	0.019	0.188	0.164	0.224	0.295 *	0.244	-0.300 *
tfG Organic P	-0.287 *	-0.188	0.378 **	-0.326 *	-0.234	0.295 *	0.695 ***	0.654 ***	-0.440 **	-0.422 **	-0.259	0.355 *
tfG HCl	-0.168	-0.149	0.030	-0.166	-0.005	0.076	-0.027	-0.044	0.008	0.041	0.045	-0.051
tfG Oxalate	-0.158	-0.045	0.134	-0.273	0.029	0.091	0.244	0.225	-0.205	-0.055	0.023	0.003
tfG Total P	-0.384 **	-0.266	0.238	-0.357 *	-0.177	0.323 *	0.305 *	0.181	-0.377 **	-0.290 *	-0.225	0.275

[a] EC = electrical conductivity in saturated H_2O extract
[b] OC = organic carbon
[c] KH = amount of water necessary to prepare the H_2O saturation extract
[d] tfG Fe-oxide P_i = transfer factor of P extractable by iron oxide impregnated filter paper
[e] tfG CAL = transfer factor of P extractable by calcium acetate lactate
[f] tfG AEM = transfer factor of P extractable by anion exchange membrane

	[g] CEC_{pot}	[h] BS	Ca	Mg	K	Al	[i] Fe_d	[i] Mn_d	[j] Fe_o	[j] Mn_o	[ij] Fe_o/Fe_d	[j] P_o/Fe_o (molar)
tfG H_2O	-0.076	0.197	0.229	0.108	-0.347 *	-0.087	-0.131	-0.254	-0.111	-0.181	-0.094	-0.045
tfG $CaCl_2$	0.067	0.339 *	0.334 *	0.296 *	-0.140	-0.199	-0.085	-0.153	-0.154	-0.150	-0.342 *	0.351
tfG LiCl	0.233	0.173	0.200	0.148	-0.359 *	-0.249	0.010	0.044	-0.031	0.012	-0.174	-0.123
[d] **tfG Fe-oxide P**	0.151	0.520 ***	0.540 ***	0.278	-0.190	-0.151	-0.157	-0.208	-0.265	-0.277	-0.440 **	0.106
tfG Olsen	-0.024	0.429 **	0.455 ***	0.214	-0.245	0.001	-0.194	-0.172	-0.306 *	-0.208	-0.468 ***	0.008
[e] **tfG CAL**	-0.004	0.065	0.087	0.061	-0.284 *	0.117	0.004	-0.047	-0.068	0.014	-0.230	-0.313 *
[f] **tfG AEM**	0.051	0.510 ***	0.535 ***	0.259	-0.242	-0.159	-0.210	-0.264	-0.341 *	-0.397 **	-0.528 ***	0.210
tfG Mehlich 3	0.240	0.448 **	0.464 ***	0.324 *	-0.298 *	-0.095	0.045	-0.102	-0.066	-0.132	-0.374 **	-0.074
tfG Bray II	0.074	0.246	0.234	0.256	-0.098	-0.054	-0.166	-0.325 *	-0.140	-0.244	0.035	0.293 *
tfG Dithionite	-0.050	0.584 ***	0.599 ***	0.263	-0.074	0.066	-0.414 **	-0.394 **	-0.547 ***	-0.471 ***	-0.581 ***	0.431 **
tfG Organic P	-0.462 ***	-0.123	-0.090	-0.365 **	0.167	0.738 ***	-0.356 *	-0.388 **	-0.255	-0.220	0.166	-0.081
tfG HCl	-0.084	-0.040	-0.040	-0.012	-0.041	0.266	-0.143	-0.012	-0.278	0.077	-0.361 **	-0.120
tfG Oxalate	-0.302 *	0.113	0.136	-0.085	0.011	0.503 ***	-0.345 *	-0.272	-0.392 **	-0.173	-0.273	-0.209
tfG Total P	-0.425 **	-0.123	-0.103	-0.259	0.112	0.540 ***	-0.372 **	-0.337 *	-0.356 *	-0.160	-0.092	-0.137

[d] tfG Fe-oxide P_i = transfer factor of P extractable by iron oxide impregnated filter paper
[e] tfG CAL = transfer factor of P extractable by calcium acetate lactate
[f] tfG AEM = transfer factor of P extractable by anion exchange membrane
[g] CEC_{pot} = potential cation exchange capa
[h] BS = base saturation
[i] Fe_d and Mn_d = dithionite-extractable Fe and Mn
[j] Fe_o, Mn_o and P_o = oxalate-extractable Fe, Mn and P

Table 19: Transfer factors from different soil P pools to wheat straw (tfS) correlated with soil parameters, significance in * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

	pH (H_2O)	pH (KCl)	[a] EC	[b] OC	$CaCO_3$	C/N (molar)	C/P (molar)	N/P (molar)	[c] KH	Clay	Silt	Sand
tfS H_2O	-0.046	-0.045	-0.168	-0.012	0.126	-0.043	0.051	0.073	-0.097	-0.011	0.110	-0.072
tfS $CaCl_2$	0.216	0.236	-0.105	0.145	0.228	-0.114	-0.065	-0.018	0.180	0.255	0.161	-0.224
tfS LiCl	0.176	0.008	-0.273	0.143	0.133	-0.234	-0.097	0.002	0.303 *	0.262	0.361 *	-0.360 *
[d] **tfS Fe-oxide P_i**	0.277	0.321 *	-0.016	0.166	0.383 **	-0.193	0.066	0.147	0.379 **	0.370 **	0.360 *	-0.406 **
tfS Olsen	-0.046	0.043	0.018	-0.144	0.047	-0.04	0.107	0.141	0.037	0.077	0.120	-0.117
[e] **tfS CAL**	-0.296 *	-0.250	0.011	-0.147	-0.143	0.051	0.054	0.028	-0.039	-0.013	-0.013	0.014
[f] **tfS AEM**	0.069	0.178	-0.039	0.036	0.335 *	-0.058	0.024	0.036	0.185	0.168	0.139	-0.168
tfS Mehlich 3	0.064	0.073	-0.052	0.147	0.148	-0.19	0.053	0.118	0.294 *	0.319 *	0.226	-0.292
tfS Bray II	0.158	0.204	0.022	0.455 ***	0.657 ***	-0.135	0.274	0.345 *	0.062	0.224	0.026	-0.112
tfS Dithionite	0.067	0.217	0.342 *	-0.003	0.210	0.127	0.325 *	0.272	0.060	0.090	0.034	-0.065
tfS Organic P	-0.291 *	-0.193	0.410 **	-0.300	-0.268	0.247	0.64 ***	0.632 ***	-0.377 **	-0.394 **	-0.260	0.346 *
tfS HCl	-0.350 *	-0.268	0.238	-0.229	-0.210	0.18	0.120	0.068	-0.114	-0.112	-0.133	0.138
tfS Oxalate	-0.351 *	-0.205	0.303 *	-0.313 *	-0.205	0.185	0.32 *	0.278	-0.276	-0.205	-0.175	0.205
tfS Total P	-0.464 ***	-0.322 *	0.369 **	-0.342 *	-0.299 *	0.339 *	0.35 *	0.233	-0.369 **	-0.340 *	-0.322 *	0.365 **

[a] EC = electrical conductivity in saturated H_2O extract
[b] OC = organic carbon
[c] KH = amount of water necessary to prepare the H_2O saturation extract
[d] tfG Fe-oxide P_i = transfer factor of P extractable by iron oxide impregnated filter paper
[e] tfG CAL = transfer factor of P extractable by calcium acetate lactate
[f] tfG AEM = transfer factor of P extractable by anion exchange membrane

	[g] CEC_{pot}	[h] BS	Ca	Mg	K	Al	[i] Fe_d	[i] Mn_d	[j] Fe_o	[j] Mn_o	[ij] Fe_o/Fe_d	[j] P_o/Fe_o (molar)
tfS H_2O	-0.112	0.081	0.120	0.010	-0.367 **	0.078	-0.084	-0.218	-0.072	-0.122	-0.096	-0.169
tfS $CaCl_2$	0.100	0.323 *	0.321 *	0.296 *	-0.206	-0.132	-0.051	-0.141	-0.133	-0.118	-0.366 **	0.242
tfS LiCl	0.314 *	0.046	0.065	0.111	-0.349 *	-0.108	0.067	0.088	0.002	0.084	-0.192	-0.228
[d] **tfS Fe-oxide P**	0.150	0.444 **	0.450 **	0.272	-0.123	0.065	-0.146	-0.113	-0.290 *	-0.158	-0.508 ***	-0.039
tfS Olsen	-0.127	0.210	0.217	0.105	-0.074	0.293 *	-0.175	-0.067	-0.286 *	-0.040	-0.397 **	-0.153
[e] **tfS CAL**	-0.062	-0.060	-0.053	-0.018	-0.126	0.274	0.000	-0.023	-0.070	0.070	-0.194	-0.340 *
[f] **tfS AEM**	-0.021	0.356 *	0.371	0.182	-0.159	0.065	-0.197	-0.173	-0.341 *	-0.259	-0.516 ***	0.031
tfS Mehlich 3	0.201	0.253	0.252	0.239	-0.177	0.119	0.103	0.008	-0.019	0.018	-0.351	-0.243
tfS Bray II	0.093	0.242	0.227	0.270	-0.097	-0.021	-0.150	-0.317 *	-0.136	-0.229	0.010	0.255
tfS Dithionite	-0.146	0.333	0.322 *	0.141	0.169	0.350 *	-0.366 **	-0.199	-0.506 ***	-0.229	-0.498 ***	0.188
tfS Organic P	-0.413 **	-0.147	-0.135	-0.307 *	0.269	0.711 ***	-0.270	-0.240	-0.209	-0.106	0.124	-0.061
tfS HCl	-0.176	-0.178	-0.206	-0.081	0.248	0.425 **	-0.122	0.103	-0.234	0.202	-0.247	-0.174
tfS Oxalate	-0.326 *	-0.083	-0.088	-0.159	0.244	0.595 ***	-0.247	-0.096	-0.294 *	0.005	-0.174	-0.211
tfS Total P	-0.402 **	-0.216	-0.226	-0.253	0.322 *	0.569 ***	-0.266	-0.152	-0.268	-0.008	-0.045	-0.132

[d] tfS Fe-oxide P_i = transferfactor of P extractable by iron oxide impregnated filter paper
[e] tfS CAL = transferfactor of P extractable by calcium acetate lactate
[f] tfS AEM = transferfactor of P extractable by anion exchange membrane
[g] CEC_{pot} = potential cation exchange capacity
[h] BS = base saturation
[i] Fe_d and Mn_d = dithionite-extractable Fe and Mn
[j] Fe_o, Mn_o and P_o = oxalate-extractable Fe, Mn and P

CURRICULUM VITAE

Vienna, September 2013

Personal data

Name	Rosemarie Wünscher
Date of Birth	January 13th, 1987
Place of Birth	Graz
Country of Birth	Austria
Nationality	Austrian

Education

Master program Crop Sciences 2010 - 2013	University of Natural Resources and Life Sciences, Vienna
Bachelor program Agricultural Sciences 2006 - 2010	University of Natural Resources and Life Sciences, Vienna

Professional experience

Tutor for *Soil Chemistry Laboratory* 2011-2012	Dr. Daniel Tunega, Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna
Tutor for *Specific Methods in Soil Analysis* 2011-2012	Dr. Axel Mentler, Institute of Soil Research, University of Natural Resources and Life Sciences, Vienna
Trainee in *Soil Science* 2010	Adelheid Spiegel, Division of Food Security Research - Sustainable Plant Production, Austrian Agency for Health and Food Safety (AGES)
Trainee in *Plant Breeding* 2009	Dr. Karl-Josef Müller Getreidezüchtungsforschung Darzau
Trainee in *Viticulture and Pomology* 2008	Franz Kaltenberger, Department of Crop Sciences, University of Natural Resources and Life Sciences, Vienna