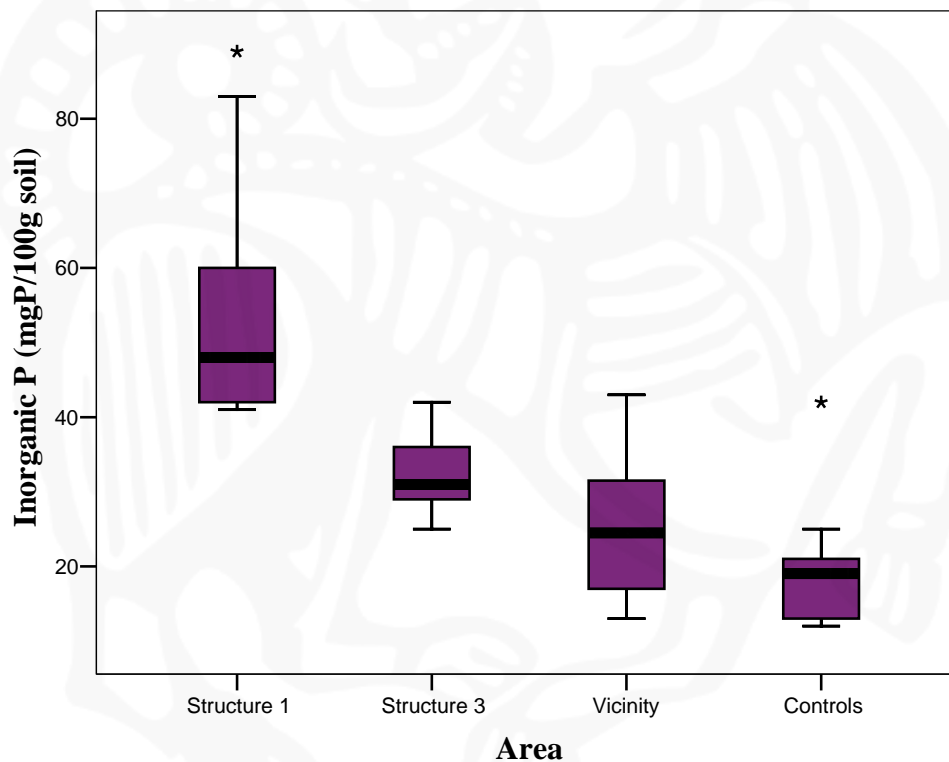
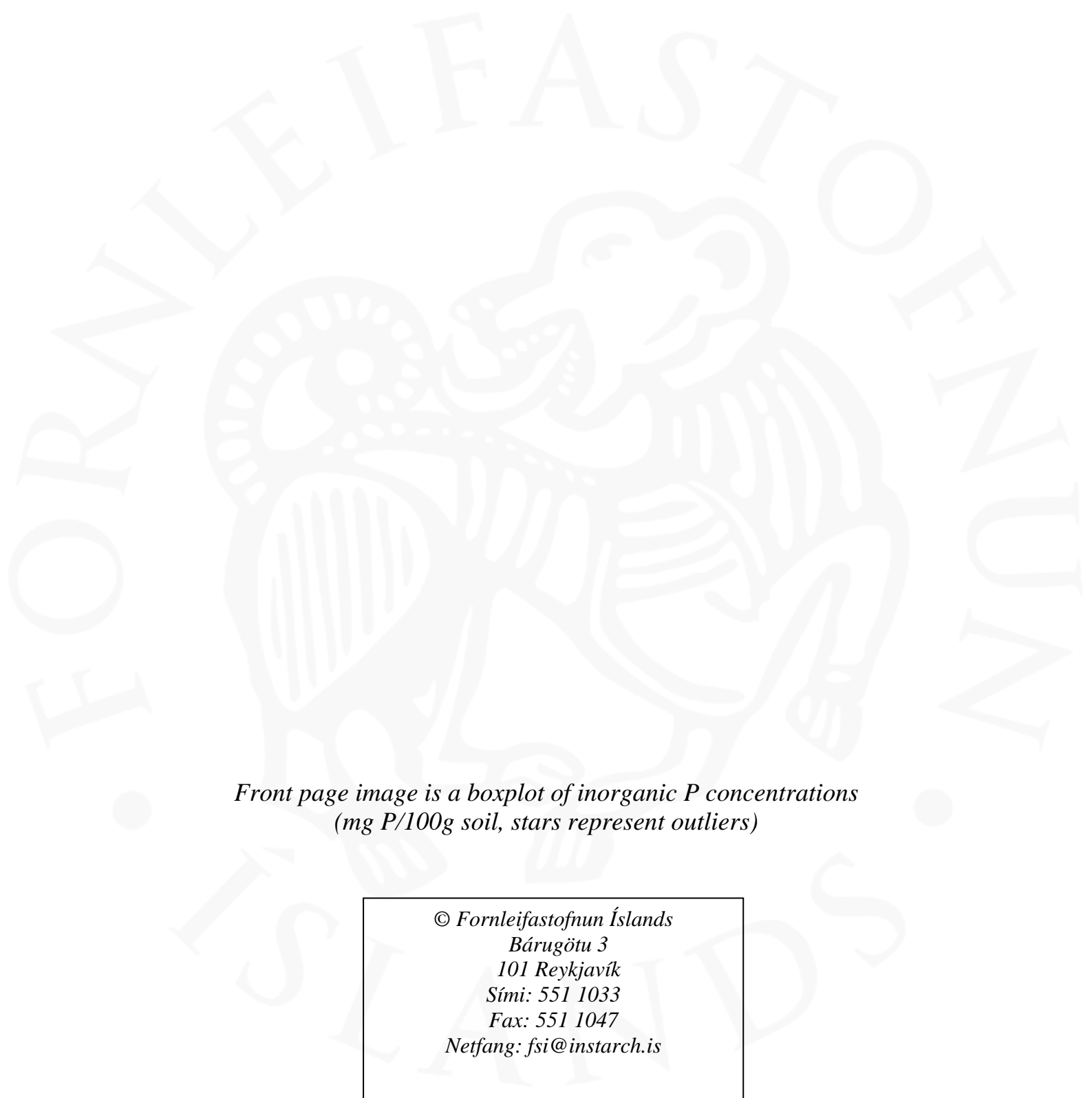


Measurements of Soil Phosphorus in Floors and Surroundings of Pálstóft, Kárahnjúkar

by Sólveig Guðmundsdóttir Beck



Fornleifastofnun Íslands
FS347-00067
Reykjavík
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*Front page image is a boxplot of inorganic P concentrations
(mg P/100g soil, stars represent outliers)*

© Fornleifastofnun Íslands
Bárugötu 3
101 Reykjavík
Sími: 551 1033
Fax: 551 1047
Netfang: fsi@instarch.is

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SOIL P IN ANDOSOLS AND ARCHAEOLOGY

Pure phosphorus is not found in nature due to its reactivity to air and many other oxygen containing compounds which are widely distributed (Zumdahl 1998, 866-869). Preservation and amounts of P in Andosols depends mostly on the mineralogy of the parent material, particle size, microbial activity and pH.

Phosphorus commonly occurs in low levels in igneous, sedimentary and metamorphic rocks as accessory apatite minerals ($\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$). Fresh tephra, e.g., contain 4-60mg P/100g soil of acid extractable P (Deer et al 1992, 663; Shoji et al 1993, 171). With advanced weathering of volcanic ash and eolian deposits amounts of acid-extractable P in Andosols tend to decrease as amorphous and poorly crystallized silicate clays, such as allophane, imogolite and ferrihydrite, crystalline silicate clays, iron and aluminium oxide clays and organic colloids are formed which bind the P in the soil (Shoji et al 1993, 171-176).

The size of these soil particles is just as important as their type. Particles that are most important in P retention are the clay and organic (humus) particles collectively called the colloidal fraction due to their extremely small size (1-2 μm in diameter) and colloid-like behavior (Brady and Weil 2004, 236). Colloids have very large surface areas which carry positive and/or negative electrostatic charges which attract or repulse substances in ionic form in soil solution as well as other colloids. These small minerals and organic colloids react with orthophosphate ions (PO_4^{3-} , HPO_4^{2-} , H_2PO_4^-) to form relatively stable inorganic Al and Fe phosphate minerals and organic phosphate compounds through phosphate sorption reactions many of which are highly resistant to normal oxidation, reduction and leaching processes (Brady and Weil 2002, 70; Eidt 1985; Shoji et al 1993, 171-176). Ligand exchange has been identified as the most important P sorption process in Icelandic Andosols where

ligands (an atom, ion, or molecule that donates one or more of its electrons to one or more central atoms or ions) coordinated with Fe og Al are exchanged with orthophosphate ions (Arnalds et al 1995; Brady and Weil 2004, 70; Shoji et al 1993, 171-176). The major reactive components in allophanic Andosols in Iceland are the amorphous and poorly crystalline aluminosilicates and organic colloids which strongly sorbe phosphate (Arnalds 2004; Brady and Weil 2002, 70; Shoji et al 1993, 171-176). Icelandic Andosols are usually finely textured (e.g. Brown Andosols are dominated by silty loams and loams) and show clear trends of more clayey horizons further away from eolian sources. They therefore have very high phosphate retention (>90%) for most horizons (Arnalds 2004, 16). Sandy horizons in Icelandic Andosols are usually single tephra layers or glacial tills underlying eolian deposits (Arnalds 2004, 12). Within sandy horizons P is susceptible to leaching from the soil profile due to lack of clay and silt sized soil colloids which are so important in the P sorption processes (Shoji et al 1993, 177) but in Iceland, while P is indeed susceptible to leaching, sandy soils still have considerable tendency to hold on to P (25-80%) due to the presence of allophane (Arnalds 2004, 16).

Ligand exchange is dependent on pH. pH is essentially a measurement of the amount of hydrogen cations (H^+ , positively charged) and hydroxide anions (OH^- , negatively charged) present in solution. When the amount of H^+ ions in a soil solution increases the pH decreases and vice versa. When the pH is 7 the solution is said to be neutral as it contains equal amounts of anions and cations (Zumdahl 1998, 223-230). Soil colloids exhibit two major sources of negative and positive charges on their surface; hydroxyls and other groups that release or accept hydrogen ions, depending on pH, or isomorphous substitution in crystal structures which is not dependent on pH. Most charges in soils rich in humus, oxides of iron and aluminum and allophane

like Andosols are pH dependent (Brady and Weil 2004, 248-249) which is why maximum phosphate sorption in Andosols occurs between pH 3-4 but the amount decreases with increasing pH, being lowest around pH 7-8 (Shoji et al 1993, 171-176). When the pH is low there are large amounts of hydrogen ions to bond with the hydroxyl groups. This frees positively charged sites on the surface of the soil colloids which the PO_4 anions can now attach themselves to but when the pH is high there are many hydroxyl groups to compete with the PO_4 anions for those spaces. The pH is generally $> 4,9$ in all Icelandic soils and around pH 6 in Gleyic and Brown Andosols (Arnalds 2000, 13).

Phosphates taken from soils by plants and animals are incorporated into a variety of organic molecules, such as inositol phosphates, phospholipids and nucleotides (adenosine triphosphate), as well as inorganic molecules like apatite in teeth, bones and shells which do not break down for a long time (Holliday and Gartner 2007, 303; Mader 2004, 892). Natural organic materials (humus) are plant residues which have been broken down and altered by microorganisms into noncrystalline organic and inorganic substances available for renewed plant uptake. During and after decomposition some soluble organic compounds are leached from soils but most are mineralized in situ or remain as refractory forms (Brady and Weil 2004, 245-247, 341; Shoji et al 1993, 154-163). Natural accumulation of organic compounds (measured as %C) in Andosols is rapid and due largely to its protection in Al-organic complexes and association with allophanes and allophane like minerals. Despite rapid decomposition of soil organic matter in soils, a relatively large fraction of original materials may remain in refractory organic forms for long periods of time (Arnalds et al 1995, 167; Brady and Weil 2004, 245-247; Holliday and Gartner 2007, 303; Schlezinger and Howes 2000, 479-480). Icelandic Andosols have a range of

<1% C (Vitrisols) up to 40% C (Histosols). Brown and Gleyic Andosols have a range of 4,5-7,5% C (Arnalds 2004, 8, table 4). Accumulation of organic materials in soils tends to lower pH because organic matter facilitates the leaching of nonacid nutrient cations by forming soluble complexes and organic matter also contains many acid functional groups which are a great source of H⁺ ions (Brady and Weil 2004, 267-268). With increasing organic content in surface horizons Icelandic Andosols show a trend towards lower pH values (down to around pH 4) although they are higher pH values than commonly reported partly due to a steady influx of eolian materials which sustain the pH levels (Arnalds et al 1995, 166; Arnalds 2004, 13-16). When organic P is mineralized to inorganic P in Andosols during decomposition it is rapidly sorbed to soil particles like allophane and imogolite and eventually precipitated as insoluble compounds if it is not taken up again by plants or leached away (Brady and Weil 2004, 245-247, 341, 433; Shoji et al 1993, 154-163). In Andosols P mainly accumulates in the upper parts of A horizons and very little leaching of P down the soil profile takes place (Shoji et al 1993, 177) despite the fact that organic matter has very little capacity to strongly fix phosphate ions because humic molecules can hide phosphate fixation sites on colloids and organic anions compete with the phosphate anions for these same sites. Organic acids can also entrap reactive Al og Fe in stable organic complexes which makes them unavalable for reaction with P ions in solution encouraging phosphate leaching in soils (Brady and Weil 2004, 441). In Andosols the organic P fraction is possibly around 35-40 % (Brady and Weil, 432, table 13.3).

When humans live in the same place over long periods of time they often leave behind them large amounts of human refuse. Human refuse can cause elevated levels of P in soils often resulting in quite large concentrations of anthropogenic P compared to natural soils. This can then be used as an indicator of human presence

because before the time of chemical fertilizers most enrichment of P in anthropological sediments and soils is associated with human activities (Proudfoot 1976, 93-94; Schlezinger and Howes 2000, 479). There are many sources of anthropological P. Human refuse, e.g. organic and inorganic discard (bone, flesh etc.) derived from animals and plants, animal and human excrement as well as burial remains and ash from fires (Guttmann et al 2005; Holliday and Gartner 2007, 307-309; Proudfoot 1976, 93-94; Schlezinger and Howes 2000, 479). Hearths, cooking features, and middens with wood ash generally have elevated levels of P as do organic residues in food preparation, consumption and disposal areas (Holliday and Gartner, 2007; Mader 2004, 892-893). As discussed above the phosphate in organic matter and excrement has an organic component which is replaced by iron or aluminum in the inorganic form in soils through decomposition due to soil microbes breaking down the organic component and thereby making the phosphate temporarily available for uptake by plants. This available phosphorus also quickly forms bonds with inorganic ions and becomes fixed in soils. Burning also removes the organic component and so P in ash is mostly in inorganic form as well as P in bone. High levels of organic P are a strong indicator of addition of organic materials, such as food waste, animal manure and night soil while high levels of inorganic P are an indicator of addition of inorganic materials, like ash and bone, and of fire (Guttmann et al 2005). Levels of organic vs inorganic phosphorus (organic fraction %) have been used by Linderholm (1997) to distinguish settlements from manured arable fields by assuming that manure elevates levels of organic P while, within settlements, the P is mostly derived from ash and bone and therefore elevates levels of inorganic P. Ash and bone discards also elevate levels of pH while organic refuse lowers pH (Holliday and Gartner 2007, 308).

METHODS

Sampling and Sample Preparation

Sampling was done systematically on a 1 m grid in structure I ($N=13$) and structure III ($N=13$) and on a 5 m grid around and underneath them ($N=16$). The control samples were taken from an undisturbed soil column of a complex of Brown and Gleyic Andosols (Arnalds and Grétarsson 2001) about ??? away from the structures excavated. Older measurements of controls from Skálholt in the southwest of the country taken from undisturbed soil columns of Gleyic and Brown Andosols (Arnalds and Grétarsson 2001) were also used for the comparison. The depth of each sample taken within the soil profile can be seen in Appendix 1. Samples taken from pure tephra layers have also been marked with a T. All control samples were taken off site to minimize the risk of contamination from human alteration of the soil chemistry as it is very high in close proximity to structures as refuse is even more likely to be deposited outside a structure than within it (Middleton and Price, 1996, 674-675). The floor in structure I was made up of thin lenses of trampled natural silts mixed with charcoal while the floor in structure III was very thin layers of natural silts mixed with decomposed hay (???). Samples were air dried and ground to a powder in a stone mortar.

Phosphate Analysis

The samples were digested in 6 M sulfuric acid (H_2SO_4) for inorganic phosphorus concentrations and burned at $550^\circ C$ for one hour and digested in 6 M sulfuric acid for total phosphorus concentrations. The inorganic and total P concentrations were determined by mixing standards with known P concentrations, and the sulfuric acid solutions from the samples, together with an ammonium molybdate reagent and measuring the light absorbance of the resulting solutions (blue in color) in a 1 cm cell at 880 nm with a spectrophotometer. The calculated difference

between an unheated and a heated sample represents the concentrations of organic P. The sulfuric acid extraction method is a modified version of the method used at the Institute of Geography, Copenhagen University developed by Mikkelsen (1997) and this method does not include the natural phosphate bound in the soils silicate structures. The results are presented in mg organic, inorganic and total P per 100 g soil.

Many different methods have been used to measure the concentrations of P in soils in archaeology and soil P dynamics are complex and still not entirely understood today. Holliday and Gartner (2007) have shown that various analytical methods used to measure soil P can produce soil P values that vary significantly for the same sample and stress that inter-site comparisons of individual soil P values are inappropriate unless the same method has been used. For this paper a rather concentrated strong sulfuric acid has been used which has a great capacity to break up soil particles and free soil P molecules. It is not clear whether the anthropological P present in the samples has been extracted completely as Andosols show very high P retention (Arnalds 2004, 16) so total P values should be interpreted with caution. However, Holliday and Gartner's (2006) research also showed that while the magnitudes of soil P values depended on acid strength and P concentrations present all the methods usually yielded similar trends through soil profiles and always identified elevated levels of soil P where they were expected.

Data Analysis

All calculations and all tables were done in Microsoft Excel[®]. Boxplots and statistical analysis were done in SPSS[®] and spatial distribution plots were done with MapInfo. The statistical analysis (Miller and Miller 2005; Þorvarðarson 2004) was comprised of:

1. Boxplots and tables that compare and help interpret the measured P values of the controls to structures I and III and the surrounding area (figures 1, 2, 3 and 4, table 1, appendix 1)
2. Calculations of summary statistics
3. Skewness/Standard Error and Kurtosis/Standard Error tests for data normality (table 2)
4. An analysis of variance (ANOVA) test (table 3)
5. Calculations of the standardized normal variable Z (appendix 1) with an arbitrary estimation of the significant level of enrichment at 2Z (2 standard deviations)
6. Figures that show the spatial distribution of the Z values (figures 5-12)

RESULTS

The Measured Phosphorus Values

An overview of the measured and calculated P values can be found in appendix 1 and in table 1. The boxplots below (figures 1-4) show a five number summary of the data which present the spread and variations of the values within the data: the lower quartile (25% of the values fall below this point), the upper quartile (75% of the values fall below this point), the median and the two extremes. The organic fraction in figure 4 gives us the percentage of organic P within the total P ($(\text{orgP}/\text{totP}) \cdot 100$).

| Area | Range of total P values | Average total P | Range of inorganic P values | Average inorganic P |
|-------------|---------------------------|--------------------------|----------------------------------|--------------------------|
| Structure 1 | 53-101 | 73 | 41-89 | 54 |
| Structure 3 | 34-73 | 57 | 25-42 | 32 |
| Visinity | 13-94 | 48 | 13-43 | 25 |
| Controls | 13-55 | 40 | 13-42 | 20 |
| Area | Range of organic P values | Average organic P values | Range of organic fraction values | Average organic fraction |
| Structure 1 | 7-32 | 19 | 10-41 | 26 |
| Structure 3 | 9-38 | 25 | 25-58 | 43 |
| Visinity | 0-52 | 19 | 2-66 | 57 |
| Controls | 0-35 | 20 | 0-75 | 43 |

Table 1 – Phosphorus ranges (mg P/100g soil and %)

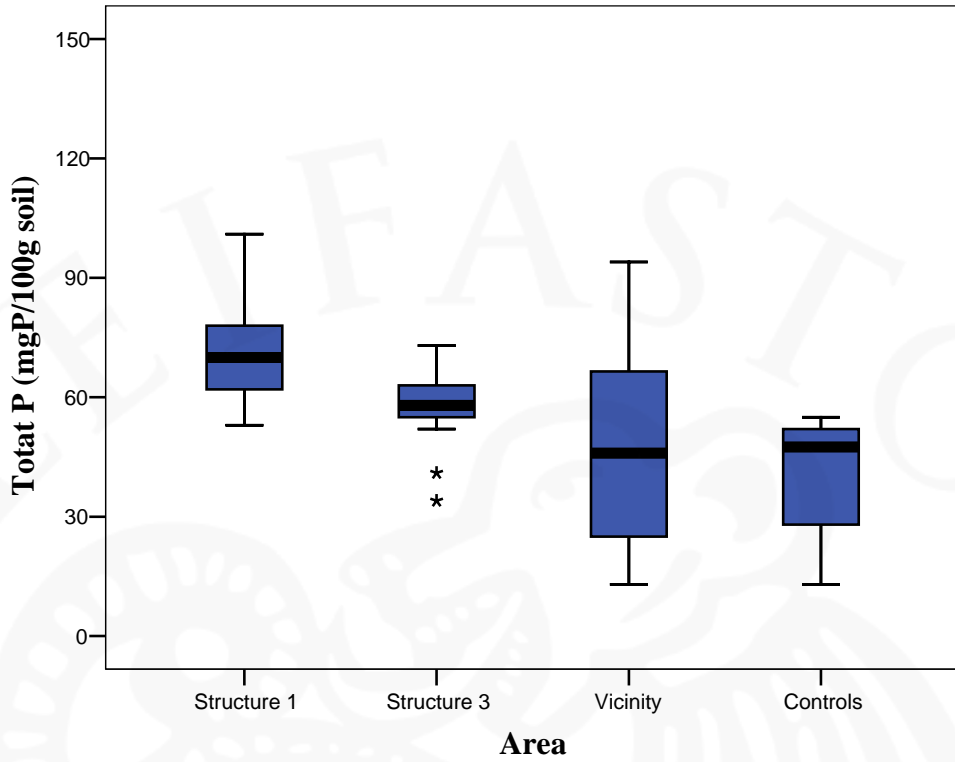


Figure 1 – A boxplot of total P concentrations (mg P/100g soil, stars represent outliers)

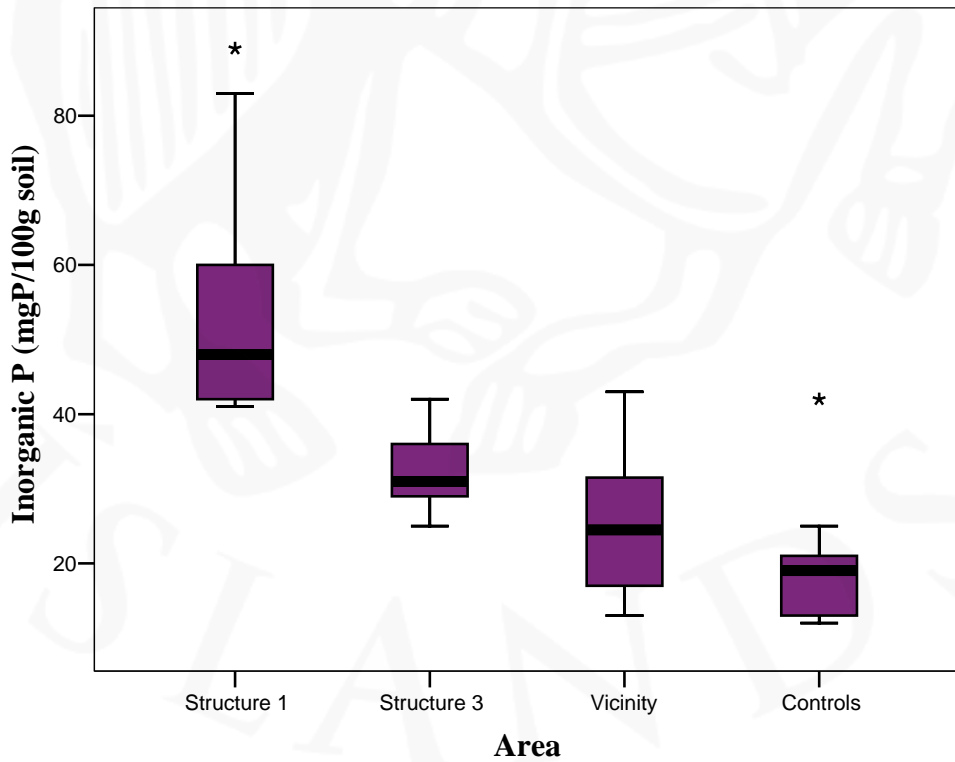


Figure 2 – A boxplot of inorganic P concentrations (mg P/100g soil, stars represent outliers)

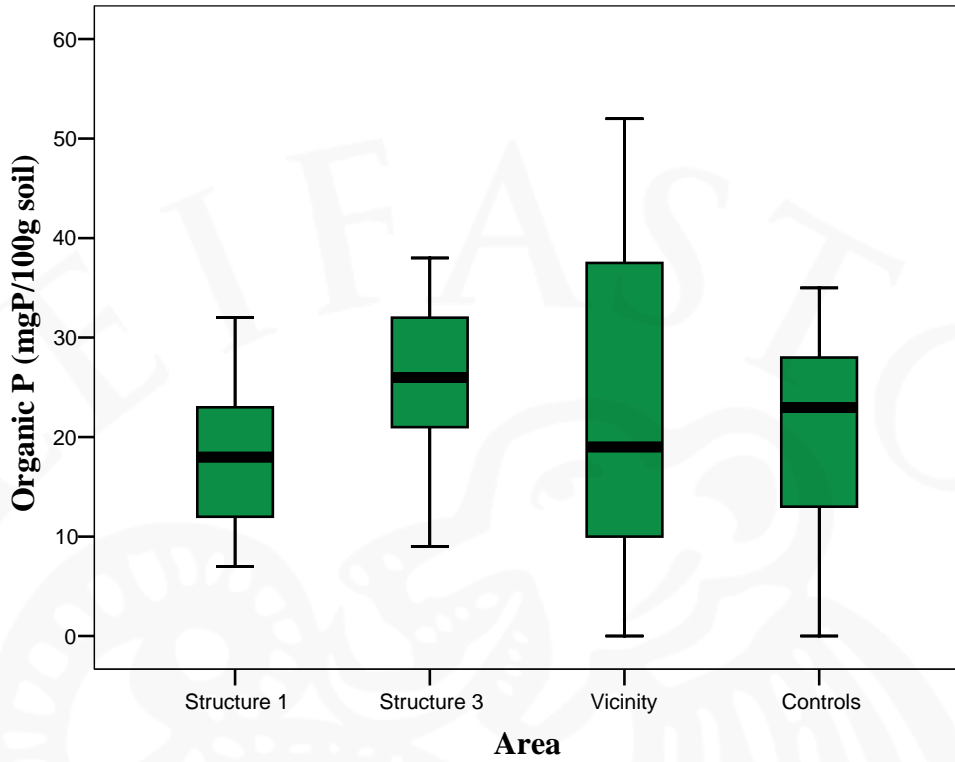


Figure 3 – A boxplot of organic P concentrations (mg P/100g soil)

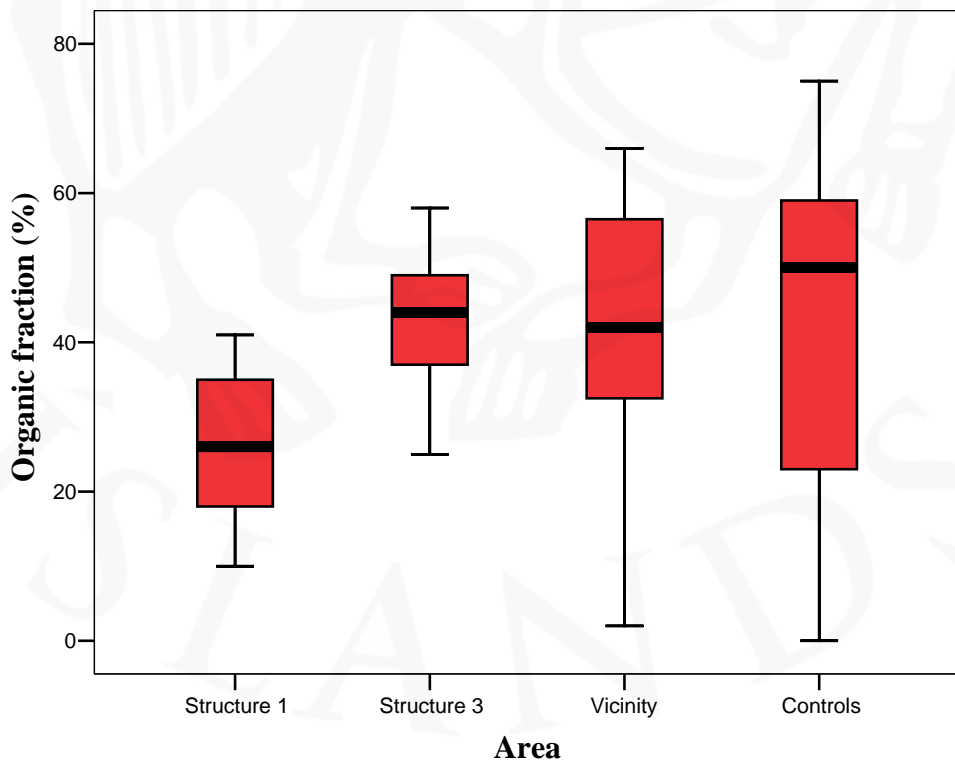


Figure 4 – A boxplot of the organic fraction (%)

In figure 1 we can see that the total P concentrations of both structures I and III are higher than the control values while the total P values of the vicinity show a very broad range and the average values in table 1 support this. In figure 2 the inorganic P concentrations of both structures are clearly higher than the control values, especially within structure I. This difference is not as clear however when inorganic P values of structure III and the controls are compared to the values measured in the vicinity of the structures where the range of values is again broad. In figure 3 and 4 it is clear that there is little or no difference in organic P and organic fraction values between structures I and III and the vicinity and the controls and the average values support this. However, the organic fraction values within structure I still seem to be slightly lower compared to the values within structure III, the vicinity and the controls as can be seen by the average values in table 1. To be certain whether there is significant statistical difference in P values between these areas an ANOVA test must be performed.

Normality Tests

To be able to compare the mean P concentrations and organic fractions of the controls versus structures I and III and the surroundings by analysis of variance (ANOVA) the data must be normally distributed. To test for data normality two simple tests based on the skewness, kurtosis and standard error statistics of the data were performed by doing the following calculations for each assemblage:

Test 1 – Skewness/Standard Error

Test 2 – Kurtosis/Standard Error

| Skewness/Standard Error | | | | |
|--------------------------------|---------------------|----------------|------------------|---------------------------|
| | <i>Inorganic P*</i> | <i>Total P</i> | <i>Organic P</i> | <i>Organic fraction %</i> |
| Structure 1 | -1,18 | 1,30 | 0,49 | -0,23 |
| Structure 3 | -0,21 | -1,43 | -0,92 | -0,74 |
| Vicinity | 0,92 | 0,39 | 0,72 | -1,28 |
| Controls | -0,25 | -1,47 | 0,78 | -1,23 |

| Kurtosis/Standard Error | | | | |
|-------------------------|---------------------|----------------|------------------|---------------------------|
| | <i>Inorganic P*</i> | <i>Total P</i> | <i>Organic P</i> | <i>Organic fraction %</i> |
| Structure 1 | -0,60 | 0,12 | -0,81 | -1,12 |
| Structure 3 | 0,11 | 0,80 | -0,26 | -0,15 |
| Vicinity | -0,85 | -0,67 | -1,04 | 0,78 |
| Controls | -0,48 | -0,42 | -0,75 | -0,41 |

*ANOVA calculated with P values after reciprocal transformation (1/x) due to negatively skewed data

Table 2 – Outcomes of the data normality tests

The outcome can be seen in table 2. Data is considered normally distributed when Skewness/Standard Error and Kurtosis/Standard Error are <2 , which means that the data for each group is normally distributed. Reciprocal transformation had to be done on the inorganic P values by dividing 1 by each value (1/x) to revert negatively skewed data into normally distributed data to be able to perform the analysis.

Analysis of variance - ANOVA (single factor)

The ANOVA test tells us whether there are significant statistical differences between the mean P concentrations and organic fractions of the controls and structures I and III and the surroundings. Null and alternative hypotheses for this test are:

H_0 = There is *no* statistically significant difference between the means of the different types of P concentrations or organic fractions within each group

H_1 = There *is* a statistically significant difference between the means of the different types of P concentrations or organic fractions within each group

With a confidence interval of 95% the p-value (value of significance) must be less than 0,05 for the H_0 hypothesis to be rejected and the H_1 hypothesis to be accepted. With the value of significance at 0,05 there is only a 5% likelihood that the H_0 hypothesis has been rejected when it should be accepted. The results of the ANOVA

tests can be seen in table 3 and the p-values that portray that there is a significant difference between phosphorus values in the designated areas are bold.

| Inorganic P (mg P/100g soil) | | | | |
|-------------------------------------|-------------|-------------|-------------|----------|
| Significance level p = 0,05 | | | | |
| | Structure 1 | Structure 3 | Vicinity | Controls |
| Structure 1 | - | - | - | - |
| Structure 3 | 0,02 | - | - | - |
| Vicinity | 0,00 | 0,01 | - | - |
| Controls | 0,00 | 0,00 | 0,02 | - |

| Total P (mg P/100g soil) | | | | |
|---------------------------------|-------------|-------------|----------|----------|
| Significance level p = 0,05 | | | | |
| | Structure 1 | Structure 3 | Vicinity | Controls |
| Structure 1 | - | - | - | - |
| Structure 3 | 0,03 | - | - | - |
| Vicinity | 0,00 | 0,17 | - | - |
| Controls | 0,00 | 0,02 | 0,20 | - |

| Organic P (mg P/100g soil) | | | | |
|-----------------------------------|-------------|-------------|----------|----------|
| Significance level p = 0,05 | | | | |
| | Structure 1 | Structure 3 | Vicinity | Controls |
| Structure 1 | - | - | - | - |
| Structure 3 | 0,14 | - | - | - |
| Vicinity | 0,26 | 0,67 | - | - |
| Controls | 0,78 | 0,27 | 0,45 | - |

| Organic fraction (%) | | | | |
|-----------------------------|-------------|-------------|----------|----------|
| Significance level p = 0,05 | | | | |
| | Structure 1 | Structure 3 | Vicinity | Controls |
| Structure 1 | - | - | - | - |
| Structure 3 | 0,01 | - | - | - |
| Vicinity | 0,01 | 0,96 | - | - |
| Controls | 0,02 | 0,97 | 0,99 | - |

Probability value p=0,05, confidence interval of 95%

When the P-value (value of significance) is less than 0,05 the H_0 hypothesis has been rejected and the H_1 hypothesis has been accepted, with a 5% likelihood that the H_0 hypothesis has been rejected when it should be accepted

Table 3 – Values of significance (p), results of the ANOVA tests

Table 3 shows that there is a significant difference between the mean P values of the areas in 13 out of 24 comparisons. According to the test there is a significant difference between the inorganic P concentrations of all the areas tested. The same is not true of the total P concentrations. There is a significant difference between the total P concentrations in Structures I and III and between the structures and the

controls however, there is no difference between the total P concentrations in Structure III and the samples taken in the vicinity of the structures nor between the control samples and the samples taken in the vicinity. The organic P concentrations show no significant difference between any of the areas sampled. The organic fraction (%) shows a significant difference between Structures I and III and between structure I and the controls. It also shows a difference between Structure I and the samples taken in the vicinity but not between Structure III and the controls nor the samples taken in the vicinity.

Spacial distribution of P concentrations and organic fractions

In order to estimate the level of enrichment of phosphorus in each of the samples taken inside structures I and III and in the nearest vicinity compared to the control samples taken outside the structures the standardized normal variable Z was calculated (appendix 2). The phosphorus values of the samples taken on site are expressed as standard deviations from the mean value of the control samples by subtracting the on site concentration values from the mean control value and dividing by the standard deviation of the mean control values. The significant level of enrichment was arbitrarily set at 2 standard deviations ($2z$) which means that there is a 95% chance that the enrichment is statistically significant.

The data represented as the standardized normal variable Z shows whether the soil is poor or rich of P compared to the mean concentrations of the controls. In figures 5-12 the Z values are plotted within and around a plan of structures I and III in order to determine the spatial distribution of the samples and whether there are any specific areas with high P concentrations which stand out within and/or around the structures. In figures 5-12 significant enrichment (chance >95%) is represented with

red dots. The gray area where the enrichment is 1-2 Z (chance of significant P enrichment between 68-95%) the dots are yellow and where the enrichment is thought statistically nonsignificant (chance < 68%) the dots are blue.

Figure 5 represents the spatial distribution of total P values (mgP/100g soil) within structures I and III. Within structure I there are six areas out of the 13 tested which show a statistically significant enrichment ($Z > 2$) in P compared to the controls while in structure III there is only one area out of the 13 tested. The total P concentrations are all rather low when compared to the controls but 25 samples out of 26 still show some level of enrichment ($Z > 0$) even if it is not very high. Only 1 sample in the southwest corner of structure I shows very little enrichment ($Z < 1$) while in structure III there are 4, 2 at the east end of the structure ($Z < 1$ and $Z < 0$) and 2 towards the west end ($Z < 1$).

Figure 6 represents the spatial distribution of total P values (mgP/100g soil) in the vicinity and from underneath structures I and III. There are only two areas of statistically significant enrichment ($Z > 2$), one is directly underneath structure I and the other is 5 m northeast of structure III. Five areas show an enrichment of $1 < Z < 2$. These areas are directly underneath structure II, directly underneath structure III, 3 m west of structure III, 4,5 m south of structure III and 10 m west of the northend of structure I.

Figure 7 represents the spatial distribution of inorganic P values (mgP/100g soil) within structures I and III. Within structure I all the areas show a statistically significant enrichment ($Z > 2$) compared to the controls. In structure III there is only one such area near the middle of the structure but there are still only two areas out of 13 that show a Z value of < 1. 10 out of 13 areas show an inorganic P enrichment of $1 < Z < 2$.

Total Phosphorus

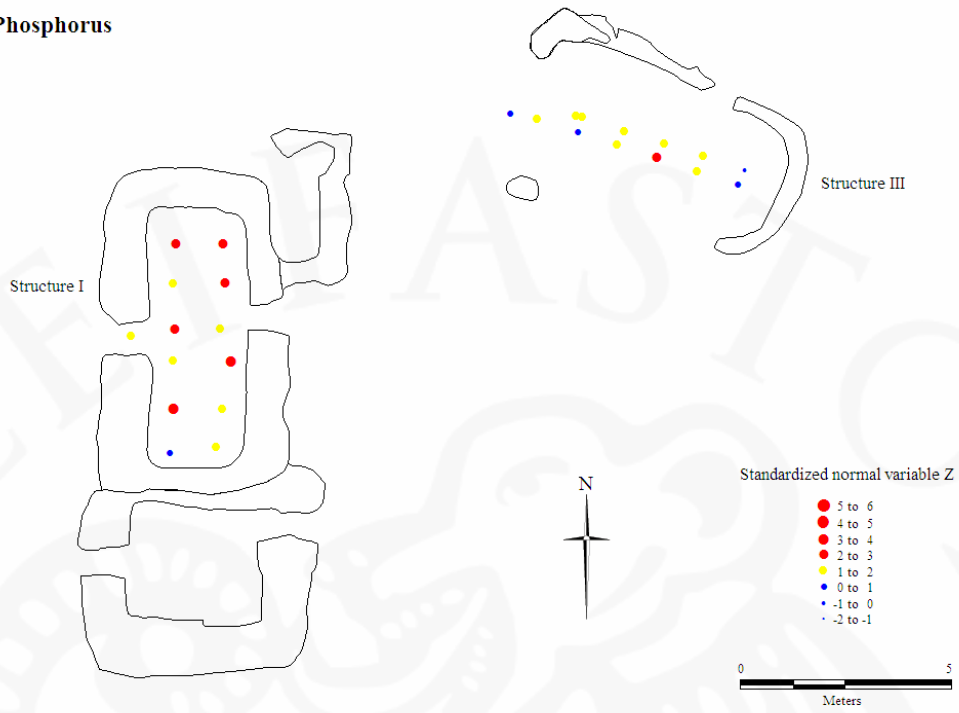


Figure 5 – Spatial distribution of samples and the standardized normal variable Z within structures I and III for total P

Total Phosphorus

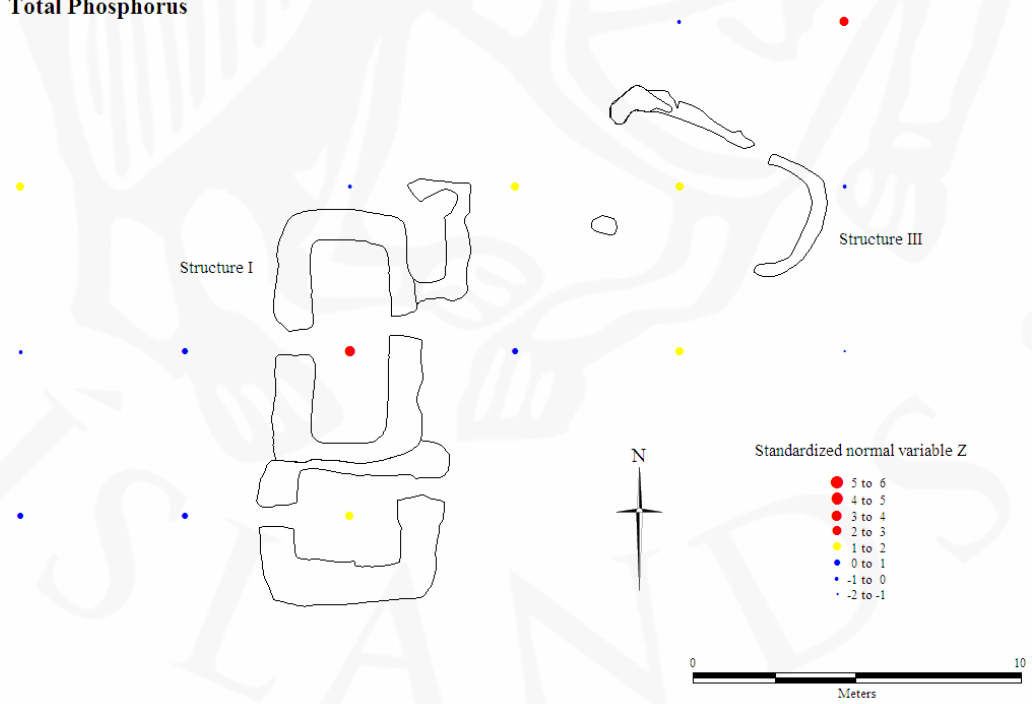


Figure 6 – Spatial distribution of samples and the standardized normal variable Z in the vicinity of structures I and III for total P

Inorganic Phosphorus

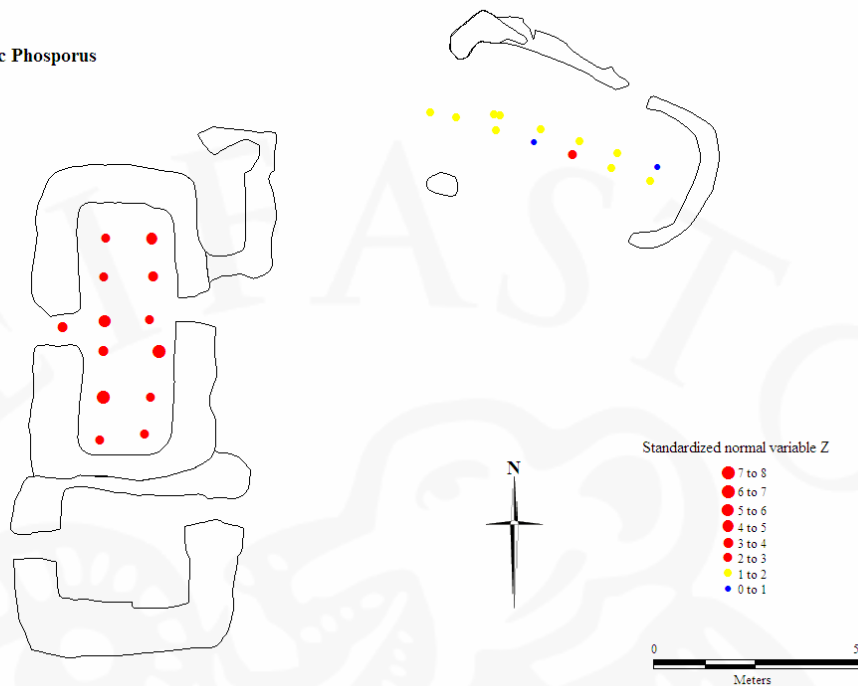


Figure 7 – Spatial distribution of samples and the standardized normal variable Z within structures I and III for inorganic P

Inorganic Phosphorus

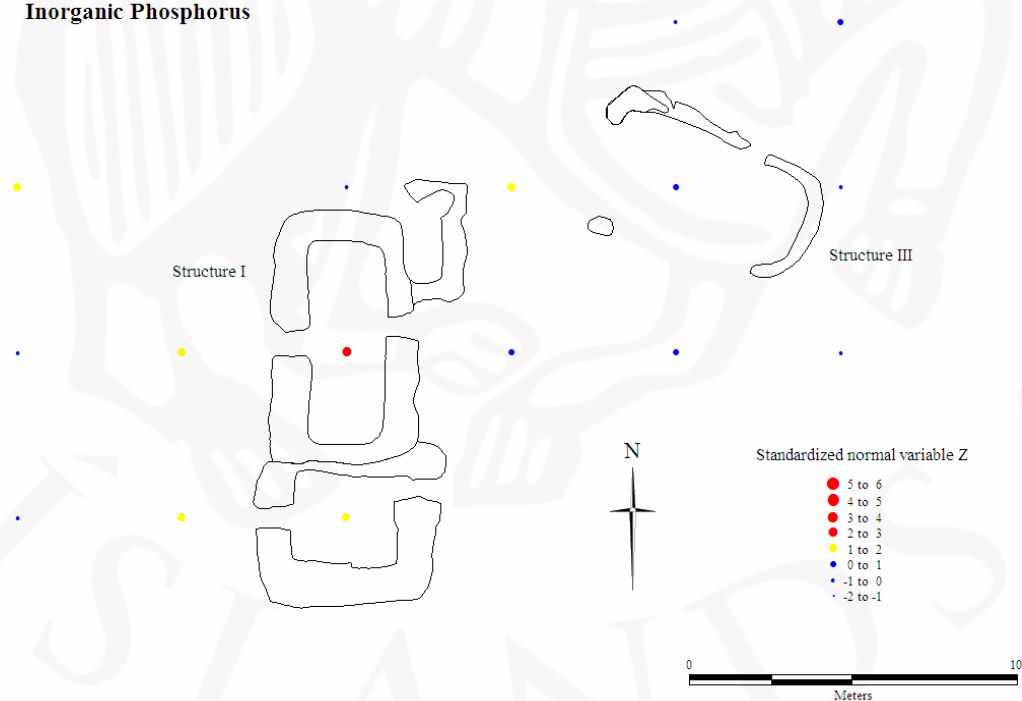


Figure 8 – Spatial distribution of samples and the standardized normal variable Z in the vicinity of structures I and III for inorganic P

Organic Phosphorus

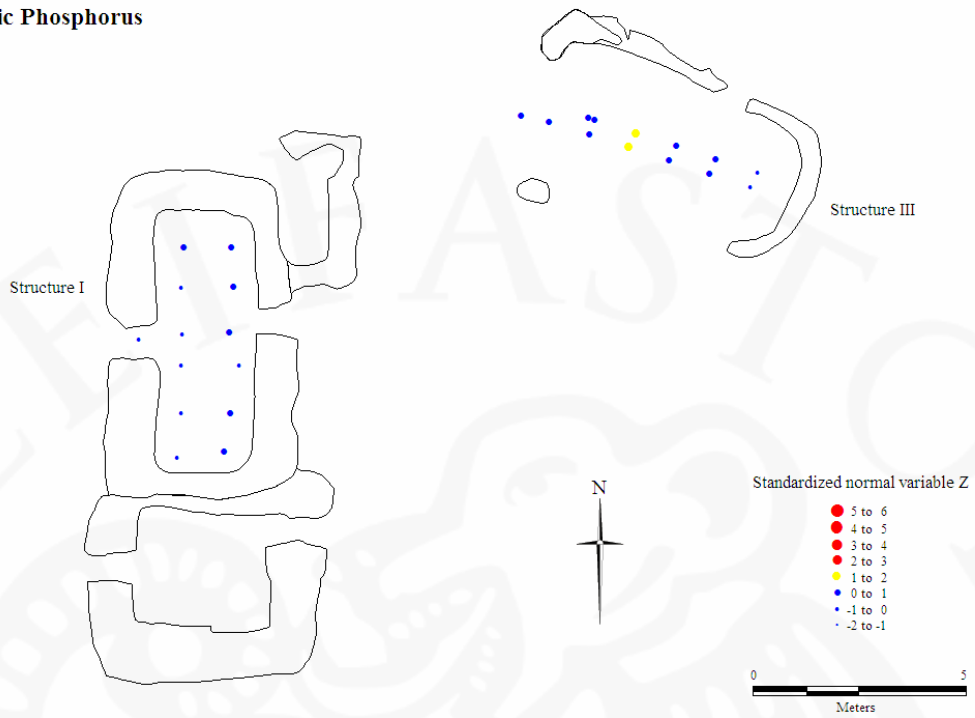


Figure 9 – Spatial distribution of samples and the standardized normal variable Z within structures I and III for organic P

Organic Phosphorus

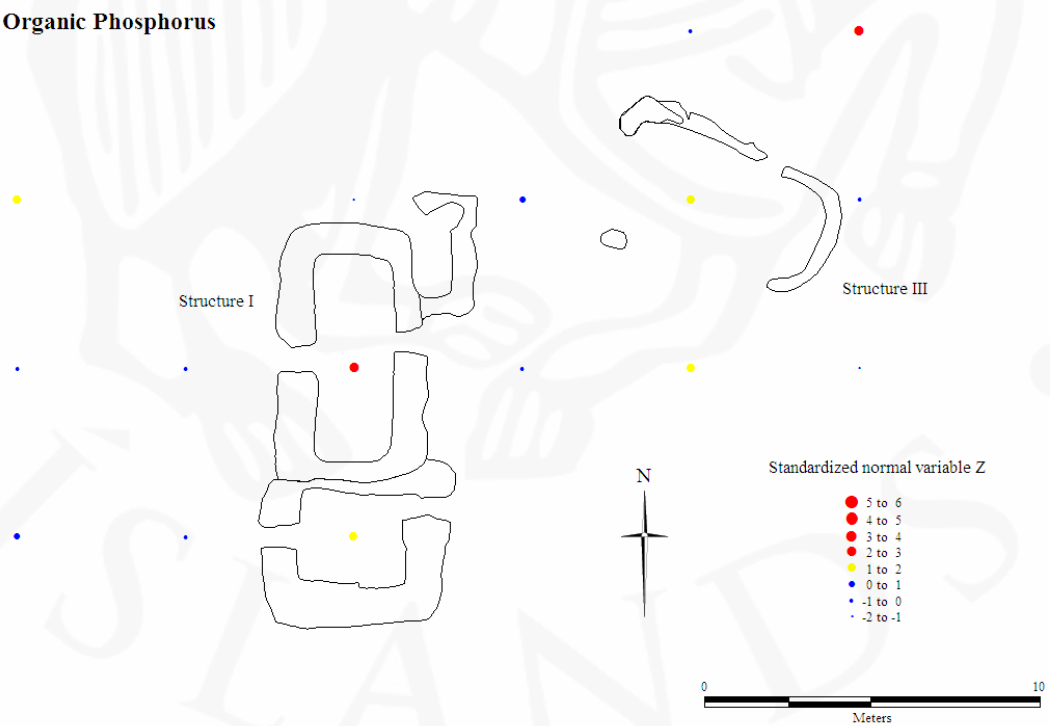


Figure 10 – Spatial distribution of samples and the standardized normal variable Z in the vicinity of structures I and III for organic P

Organic Fraction

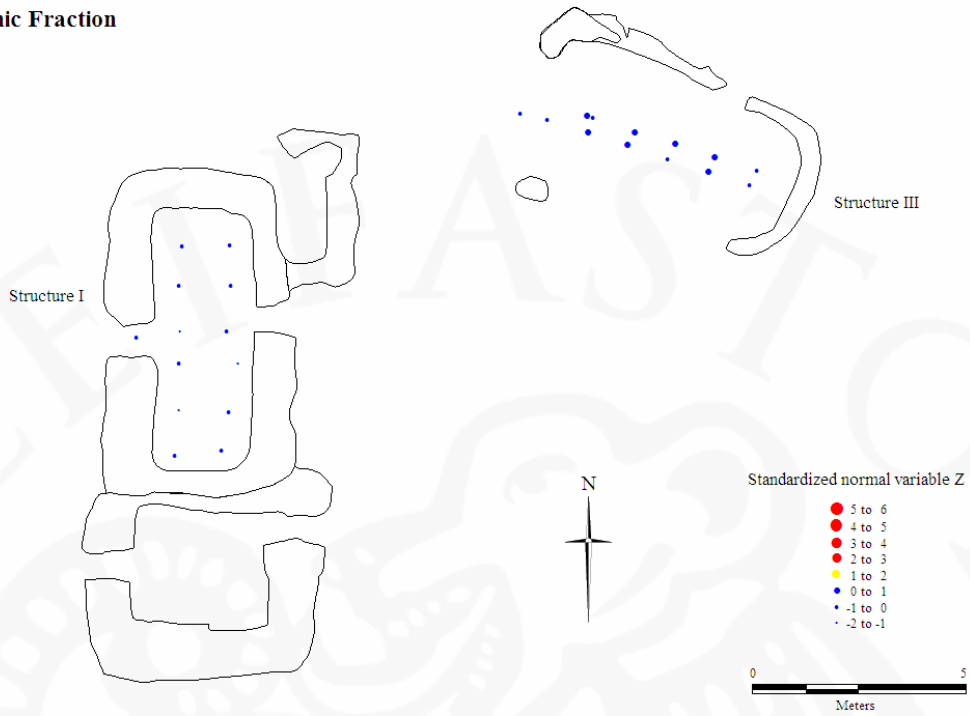


Figure 11 – Spatial distribution of samples and the standardized normal variable Z within structures I and III for the organic fraction

Organic Fraction

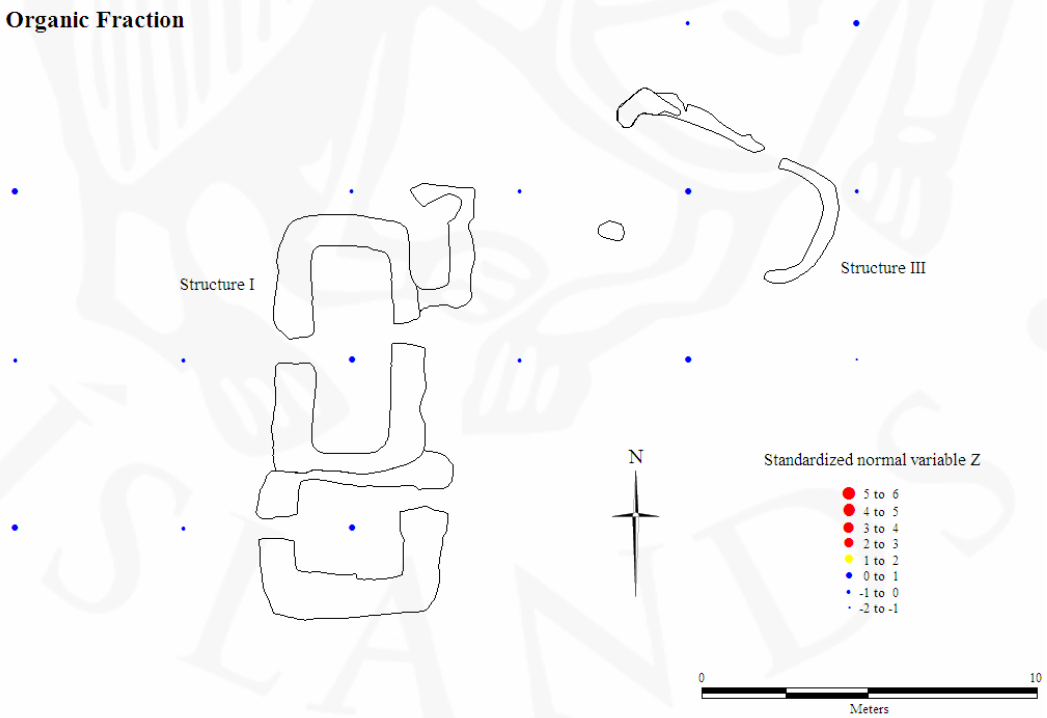


Figure 12 – Spatial distribution of samples and the standardized normal variable Z in the vicinity of structures I and III for the organic fraction

Figure 8 represents the spatial distribution of inorganic P values (mgP/100g soil) in the vicinity and from underneath structures I and III. Only 1 area shows statistically significant enrichment ($Z > 2$) in inorganic P and that area is directly underneath structure I. Five areas show an enrichment of $1 < Z < 2$. These areas are directly underneath structure II, 3 m west of structure II opposite its entrance, 2-2,5 m west of structure I opposite its entrance, 3 m west of structure III and 10 m west of the northend of structure I.

Figure 9 represents the spatial distribution of organic P values (mgP/100g soil) within structures I and III. Within structure I none of the areas show much enrichment ($Z > 1$) compared to the controls. In structure III there are two areas that show an enrichment of $1 < Z < 2$ towards the middle of the structure but there is no statistically significant enrichment ($Z > 2$).

Figure 10 represents the spatial distribution of organic P values (mgP/100g soil) in the vicinity and from underneath structures I and III. There are two places that show a statistically significant enrichment in organic P, one is directly underneath structure I and the other is 5 m northeast of structure III. Four areas show an enrichment of $1 < Z < 2$. These areas are directly underneath structure II, directly underneath structure III, 3 m south of structure III and 10 m west of the northend of structure I.

Figures 11 and 12 represent the spatial distribution of organic fraction values within, underneath and in the vicinity of structures I and III. In these figures there is no area that shows a significant difference in organic fraction ($Z > 1$) from the controls. This is not what the ANOVA tests told us above as there it suggested a significant difference between structure I and structure III, the vicinity and the controls.

However, there is still a hint of a difference between the two structures as all the Z values in structure I are <0 while 7 out of 13 areas show a Z value of $0 < Z < 1$. The difference between the structures lies in the fact that the percentages in structure I are lower than in the controls, the vicinity and structure III and so they are not represented properly through the standardized normal variable Z.

INTERPRETATIONS

Controls

The controls for this project were taken from complexes of Gleyic and Brown Andosols near Pálstóft and the Skálholt excavation sites. The samples were taken from different depths in three profiles from different horizons. The total P measurements of these samples all turned out to be below the total P limit of 4-60 mg P/100g soil of acid extractable P in fresh tephra discussed in Sohji et al (1993, 171), the highest being 55 mg total P/100g soil. Gleyic and Brown Andosols hold on to P very tightly, as it forms strong bonds with inorganic and organic compounds in the soil, so high P depletion in the control samples is unlikely even if the pH levels (~6 for Brown and Gleyic Andosols in Arnalds 2000, 13) suggests more P available for plant uptake.

Structure I

In Structure I the total P enhancement was clearest. The highest values were between 81 and a 101 mg P/100 g soil but they were not many. Compared to values from middens and soils from Neolithic to Late Iron Age Toft Ness, Scotland where the total P levels were from around 200 to 1400 mg total P/100 g soil (Guttmann et al 2006, 86) these levels are not high. This low input of P could suggest a very short

occupation span although cleaning of areas can also cause low levels of P where they are not expected. Measurements of inorganic P in all the areas sampled in Structure I showed a statistically significant enrichment ($Z > 2$) and the organic fraction (%) showed that most of them contain a somewhat larger inorganic P component than most of the controls and the samples taken in the vicinity. This suggests that while the total P values in the soil are not very high the enhancement is more likely to be anthropological rather than natural as rules of P input are different within buildings than out in nature and high levels of inorganic P are a good indicator of addition of inorganic materials, like ash and bone, and of fire. The fact that the soil layer contained charcoal supports this. Ash and bone discards elevate levels of pH (Holliday and Gartner 2007, 308) which could enhance leaching of nutrients but as the soils sampled were mostly natural silts with high capacity to hold P in the soil this influence would not have significant effects on the total P values.

As samples were not taken on a smaller grid and due to the low levels of P there are no clear patterns of high or low P concentrations within the structure. Total P values are highest inside the entrance on the westside of the structure and to the far right of that entrance, to the left and right of the entrance on the eastside of the structure and at the north end. There is one poorly enriched area in the southwest corner which might suggest furniture or something else that hindered the deposition of P. The original source of the P (bone, dung, hey etc..) must be found by other means such as micromorphology.

Structure III

The enhancement of total P is even more unclear in Structure III than it was in Structure I. The highest values were between 60-70 mg total P/100 g soil and only one

area in the middle of the structure turned out to be significantly enhanced. There is more enrichment of inorganic P than organic P within the structure but the organic fraction (%) is still noticeably higher than in structure I and more like the controls and the samples taken in the vicinity. This would suggest that there has been much less input of inorganic P in Structure III than Structure I and the absence of charcoal and bone from the soil support this. Some of the inorganic P measured could have been formed from the breakdown of organic P due to microbes and weathering. Heightened levels of organic P are a strong indicator of addition of organic materials, such as food waste and animal manure and this could suggest that there was more input of organic P in structure III than in structure I but the P levels are just too low to be sure although the presence of decomposed hay in the soil does support it. Organic refuse lowers pH (Holliday and Gartner 2007, 308) which helps prevent leaching of nutrients and the soil is mostly comprised of natural silts so it is unlikely that much of the P has been lost and should still be bound in organic and inorganic compounds. This low input of P could suggest a very short occupation span and/or regular cleaning of areas which can also cause low levels of P where they are not expected. E.g. if this structure was some sort of shelter for animals it would have to be cleaned out regularly which would prevent the accumulation of P to a certain degree. The thinness of the soil layer suggests that if the structure was an animal stall the dung was not allowed to accumulate.

The occupation layer was so thin that good samples could not be taken at one meter intervals within the whole structure. The distribution of the samples taken does not tell us much about specific P enhancement areas except that there seems to be more P towards the middle of the structure than towards its east and west ends.

Vicinity

It was immediately clear from the boxplots in figures 1-4 that some of the areas sampled in the vicinity of Structures I and III had to have enhanced P levels while others were seemingly unaffected due to the broad range of values it showed in all types of P. Most of the enriched areas are underneath or close to the structures but 7 out of 16 areas sampled show little or no enhancement at all ($Z < 1$). The three enhanced samples taken underneath the structures can be dismissed as due to movement of P down profile from the floors above during and after abandonment but they do show us that a part of the P does move down profile. This also means that the other enriched areas not underneath structures could signify some movement of P down profile from P rich soils or sediments above but what those sediments are comprised of is impossible to predict precisely unless they are still present above.

The only area unconnected with the structures that shows a statistically significant enrichment is 5 m northeast of structure III and it is enriched in organic P. This area could be a site where there was a dung heap or some sort of a midden rich in organic waste. 3 m south of the structure there is an area slightly enhanced in organic P which could also have been the place of a dung heap, a mixture of organic and inorganic middenwaste or maybe there was a pathway there that people and livestock regularly travelled which lay northwest between Structures III and IV 2,5 m west of Structure III where there is also an area slightly enriched in inorganic P. There it would be unlikely to find a midden or a dung heap as there would have been need to travel between the two buildings unimpeded unless a long time passed between the building of Structure I and Structure III.

Two areas closely west of structure I opposite the entrances to structures I and II are slightly enhanced in inorganic P which might be due to debris carried to and from structures I and II under shoes or perhaps from ash rich middens or other inorganic waste disposal from these same structures.

About 10 m west of the northend of structure I there is an area enhanced in inorganic and organic P which also could have been the place of a midden or a dung heap.

CONCLUSIONS

We have established that while enrichment of P is present it is rather low which makes it difficult to detect any clear patterns of significant enrichment areas within the structures. The enhancement is more likely to be anthropological rather than natural as rates of P input are different within buildings than out in nature. This low input of P suggests a very short occupation span although cleaning of areas can also cause low levels of P where they are not expected. The enhancement was clearest in structure I and probably largely due to addition of inorganic materials like ash. The enhancement of P was more unclear in structure III but there are hints that there was less input of inorganic P than in structure I. It was suggested that there was more input of organic P in structure III than in structure I but the P levels are just too low to be sure although the presence of decomposed hay in the soil does support it. There were also a few areas outside the buildings that showed some enrichment in P in the undisturbed soil possibly due to the movement of P down profile from an anthropological source. It is, however, impossible to predict the nature of these sources precisely unless they are still present above and it must be stressed that measurements of P values can not tell us the exact source of P and this data should be

viewed alongside other data such as descriptions of the soils micromorphology, organic C% and pH to accurately interpret the use of the structures.

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Appendices

Appendix 1 - Phosphate concentrations (mgP/100g soil) and the organic fraction (%)

| Sample No | Area | x | y | Inorganic P (mgP/100 g soil) | Total P (mgP/100 g soil) | Organic P (mgP/100 g soil) | Organic fraction (%) |
|-----------|----------|---------------------|--------|------------------------------|--------------------------|----------------------------|----------------------|
| 11 | 1 | 94,34 | 107,58 | 41 | 53 | 12 | 24 |
| 12 | 1 | 94,43 | 108,63 | 83 | 96 | 13 | 14 |
| 13 | 1 | 94,44 | 109,76 | 53 | 68 | 15 | 22 |
| 14 | 1 | 94,46 | 110,48 | 67 | 74 | 7 | 10 |
| 15 | 1 | 94,44 | 111,57 | 44 | 61 | 18 | 29 |
| 16 | 1 | 94,50 | 112,50 | 46 | 78 | 32 | 41 |
| 17 | 1 | 95,44 | 107,72 | 41 | 62 | 21 | 34 |
| 18 | 1 | 95,60 | 108,62 | 42 | 70 | 28 | 40 |
| 19 | 1 | 95,81 | 109,74 | 89 | 101 | 12 | 12 |
| 20 | 1 | 95,56 | 110,51 | 41 | 64 | 23 | 36 |
| 21 | 1 | 95,65 | 111,58 | 50 | 77 | 27 | 35 |
| 22 | 1 | 95,62 | 112,51 | 60 | 81 | 21 | 26 |
| 23 | 1 | 93,44 | 110,35 | 48 | 59 | 10 | 18 |
| 44 | 3 | 107,96 | 114,26 | 25 | 34 | 9 | 25 |
| 45 | 3 | 106,98 | 114,58 | 31 | 63 | 33 | 51 |
| 46 | 3 | 106,06 | 114,88 | 29 | 62 | 32 | 52 |
| 47 | 3 | 105,12 | 115,16 | 36 | 69 | 34 | 49 |
| 48 | 3 | 104,13 | 115,50 | 37 | 58 | 21 | 37 |
| 49 | 3 | 103,98 | 115,54 | 30 | 58 | 29 | 49 |
| 50 | 3 | 107,80 | 113,92 | 29 | 41 | 12 | 30 |
| 51 | 3 | 106,84 | 114,22 | 30 | 56 | 26 | 46 |
| 52 | 3 | 105,89 | 114,54 | 42 | 73 | 31 | 43 |
| 53 | 3 | 104,94 | 114,86 | 28 | 66 | 38 | 58 |
| 54 | 3 | 104,02 | 115,15 | 31 | 55 | 24 | 44 |
| 55 | 3 | 103,06 | 115,45 | 36 | 58 | 21 | 37 |
| 56 | 3 | 102,42 | 115,59 | 32 | 52 | 21 | 39 |
| 111 | Visinity | 85 | 105 | 18 | 42 | 24 | 57 |
| 112 | Visinity | 85 | 110 | 16 | 24 | 9 | 35 |
| 113 | Visinity | 85 | 115 | 30 | 67 | 38 | 56 |
| 114 | Visinity | 90 | 105 | 33 | 48 | 15 | 31 |
| 115 | Visinity | 90 | 110 | 30 | 44 | 14 | 32 |
| 116 | Visinity | 95 | 105 | 36 | 69 | 33 | 48 |
| 117 | Visinity | 95 | 110 | 43 | 94 | 52 | 55 |
| 118 | Visinity | 95 | 115 | 18 | 24 | 6 | 26 |
| 119 | Visinity | 100 | 110 | 23 | 40 | 17 | 42 |
| 120 | Visinity | 100 | 115 | 36 | 57 | 21 | 37 |
| 121 | Visinity | 105 | 110 | 23 | 66 | 43 | 66 |
| 122 | Visinity | 105 | 115 | 27 | 64 | 37 | 58 |
| 123 | Visinity | 105 | 120 | 16 | 24 | 8 | 33 |
| 124 | Visinity | 110 | 110 | 13 | 13 | 0 | 2 |
| 125 | Visinity | 110 | 115 | 15 | 26 | 11 | 42 |
| 126 | Visinity | 110 | 120 | 26 | 74 | 48 | 64 |
| 1 | Controls | 43 cm below surface | | 15 | 28 | 14 | 48 |
| 2 | Controls | 98 cm below surface | | 25 | 52 | 27 | 52 |
| 209* | Controls | 118 cm below surfac | | 13 | 13 | 0 | 0 |
| 211* | Controls | 94 cm below s. | T | 13 | 13 | 0 | 0 |
| 213* | Controls | 50 cm below surface | | 18 | 52 | 34 | 66 |
| 214* | Controls | 24 cm below surface | | 20 | 39 | 19 | 48 |
| 216* | Controls | 138 cm below surfac | | 12 | 47 | 35 | 75 |
| 217* | Controls | 90 cm below surface | | 21 | 49 | 28 | 57 |
| 218* | Controls | 55 cm below s. | T | 42 | 55 | 13 | 23 |
| 219* | Controls | 34 cm below surface | | 20 | 48 | 28 | 59 |

* measurements of controls from an unpublished dissertation (Beck, 2005)

Appendix 2 – Standardized Normal Variable Z

| Sample No | Area | x | y | Z for Inorganic P | Z for Total P | Z for Organic P | Z for Organic Fraction |
|-----------|-------------|--------|--------|-------------------|---------------|-----------------|------------------------|
| 11 | Structure 1 | 94,34 | 107,58 | 2,30 | 0,83 | -0,57 | -0,74 |
| 12 | Structure 1 | 94,43 | 108,63 | 6,99 | 3,51 | -0,49 | -1,10 |
| 13 | Structure 1 | 94,44 | 109,76 | 3,72 | 1,78 | -0,37 | -0,79 |
| 14 | Structure 1 | 94,46 | 110,48 | 5,23 | 2,14 | -0,97 | -1,26 |
| 15 | Structure 1 | 94,44 | 111,57 | 2,66 | 1,34 | -0,18 | -0,54 |
| 16 | Structure 1 | 94,50 | 112,50 | 2,88 | 2,39 | 0,97 | -0,05 |
| 17 | Structure 1 | 95,44 | 107,72 | 2,31 | 1,37 | 0,10 | -0,33 |
| 18 | Structure 1 | 95,60 | 108,62 | 2,52 | 1,90 | 0,61 | -0,13 |
| 19 | Structure 1 | 95,81 | 109,74 | 7,72 | 3,81 | -0,63 | -1,19 |
| 20 | Structure 1 | 95,56 | 110,51 | 2,36 | 1,54 | 0,28 | -0,25 |
| 21 | Structure 1 | 95,65 | 111,58 | 3,35 | 2,33 | 0,56 | -0,29 |
| 22 | Structure 1 | 95,62 | 112,51 | 4,46 | 2,56 | 0,08 | -0,65 |
| 23 | Structure 1 | 93,44 | 110,35 | 3,16 | 1,18 | -0,73 | -0,96 |
| 44 | Structure 3 | 107,96 | 114,26 | 0,61 | -0,35 | -0,86 | -0,67 |
| 45 | Structure 3 | 106,98 | 114,58 | 1,23 | 1,48 | 0,98 | 0,32 |
| 46 | Structure 3 | 106,06 | 114,88 | 1,07 | 1,36 | 0,95 | 0,35 |
| 47 | Structure 3 | 105,12 | 115,16 | 1,75 | 1,83 | 1,06 | 0,22 |
| 48 | Structure 3 | 104,13 | 115,50 | 1,90 | 1,15 | 0,11 | -0,24 |
| 49 | Structure 3 | 103,98 | 115,54 | 1,08 | 1,17 | 0,70 | 0,25 |
| 50 | Structure 3 | 107,80 | 113,92 | 1,01 | 0,11 | -0,57 | -0,49 |
| 51 | Structure 3 | 106,84 | 114,22 | 1,16 | 1,03 | 0,47 | 0,13 |
| 52 | Structure 3 | 105,89 | 114,54 | 2,44 | 2,07 | 0,88 | 0,00 |
| 53 | Structure 3 | 104,94 | 114,86 | 0,91 | 1,64 | 1,41 | 0,56 |
| 54 | Structure 3 | 104,02 | 115,15 | 1,22 | 0,94 | 0,33 | 0,04 |
| 55 | Structure 3 | 103,06 | 115,45 | 1,84 | 1,13 | 0,13 | -0,22 |
| 56 | Structure 3 | 102,42 | 115,59 | 1,32 | 0,78 | 0,06 | -0,13 |
| 111 | Vicinity | 85 | 105 | -0,23 | 0,12 | 0,31 | 0,55 |
| 112 | Vicinity | 85 | 110 | -0,44 | -0,94 | -0,86 | -0,29 |
| 113 | Vicinity | 85 | 115 | 1,08 | 1,71 | 1,37 | 0,50 |
| 114 | Vicinity | 90 | 105 | 1,42 | 0,49 | -0,38 | -0,44 |
| 115 | Vicinity | 90 | 110 | 1,11 | 0,28 | -0,43 | -0,40 |
| 116 | Vicinity | 95 | 105 | 1,75 | 1,81 | 1,03 | 0,21 |
| 117 | Vicinity | 95 | 110 | 2,53 | 3,40 | 2,47 | 0,46 |
| 118 | Vicinity | 95 | 115 | -0,18 | -0,94 | -1,04 | -0,65 |
| 119 | Vicinity | 100 | 110 | 0,38 | 0,02 | -0,24 | -0,04 |
| 120 | Vicinity | 100 | 115 | 1,76 | 1,05 | 0,08 | -0,22 |
| 121 | Vicinity | 105 | 110 | 0,30 | 1,61 | 1,80 | 0,87 |
| 122 | Vicinity | 105 | 115 | 0,80 | 1,49 | 1,30 | 0,56 |
| 123 | Vicinity | 105 | 120 | -0,42 | -0,97 | -0,91 | -0,37 |
| 124 | Vicinity | 110 | 110 | -0,78 | -1,65 | -1,51 | -1,57 |
| 125 | Vicinity | 110 | 115 | -0,52 | -0,84 | -0,69 | -0,03 |
| 126 | Vicinity | 110 | 120 | 0,72 | 2,13 | 2,15 | 0,82 |

Significant level of enrichment was arbitrarily set at 2 standard deviations (2z)