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Effects of wood ash on soil fertility and plant performance in southwestern Kenya

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Abstract

A field experiment was conducted in Kisii county, southwestern Kenya from February to May 2017. The purpose of the study was to examine the effect of wood ash on soil pH, soil nutrient content and productivity of common bean (*Phaseolus vulgaris* L.) and compare it to effects from mineral fertilizer (Diammonium phosphate, DAP) application and liming using calcium carbonate, $CaCO_3$. Two weeding approaches with different timings were also included in the study. The experiment was two-factorial with six fertilizer/lime treatments (recommended dose of mineral fertilizer, mineral fertilizer dose used by farmers, mineral fertilizer dose used by farmers with lime, lime only, wood ash and a control where no amendments were made) and two weeding treatments (early and farmers practice) replicated four times. Soil samples were collected before experiment establishment and four weeks after the experiment was established. Data was taken on soil pH, available P, exchangeable base cation content, CEC and BS. Parameters for plant growth and development recorded were emergence, days to developmental stage V4 and R1, number of flowers and pods, bean yield and plant biomass. This was collected throughout the growing season. Data were analysed using ANOVA and Spearman's correlation coefficient.

The soil pH after treatments was found to be significantly higher in the ash treatment compared to the control and the treatments where only mineral fertilizer and no lime was applied. Lime application had no significant effect on the soil pH. However, base saturation was higher in the treatments where lime was applied than in the other treatments. No significant effects by the different treatments were recorded on available P or exchangeable base cations. The number of flowers and pods per plant was higher in plots treated with ash than in those treated with lime. The harvested plant biomass was lower in the lime treatment than in the other treatments. No significant differences were found in bean yield. Plant performance did not differ between weeding treatments, nor were there any significant interactions between fertilizer/lime treatment and weeding approach. Based on these results ash successfully increased soil pH. There are also indications that wood ash can provide other nutrients to meet the requirement of beans when grown under these conditions. Studies performed over a longer period of time would be required to see long term effects on soil pH, nutrient status and plant performance.

Keywords: Fertilization, lime, nutrient depletion, soil acidification, smallholder farmers, *Phaseolus vulgaris*, Kenya.

Popular scientific summary

By ratifying the new UN global sustainable development goals (SDGs) in 2016, the world has taken on the ambitious task of ending hunger and promoting sustainable agriculture until year 2030. In that process of reaching these goals, one important issue to address will be soil fertility, or the lack thereof. Poor soil fertility is a major yield-limiting factor globally. Soil fertility can be understood as the ability of the soil to provide the conditions necessary for plant growth and yield. Two processes lowering the fertility of soil are nutrient depletion and acidification. These processes are often enhanced in areas where population density is high, cultivation is intensive and farming is done mainly by smallholder farmers with limited access to fertilizers and inputs for soil improvement. Kisii county, located in southwestern Kenya, where this study was performed is one example of such an area.

In the search for farming strategies working to sustain and improve soil fertility while also being affordable to farmers with limited resources, use of wood ash is sometimes discussed. Wood ash contains many important plant nutrients such as potassium (K) and phosphorus (P) and can be used as a fertilizer. It also has the ability to increase soil pH in acidic soils. That can be of great importance in areas where soils are old and weathered, and therefore prone to acidification. Such soils are abundant in big parts of south Saharan Africa.

With this background, the aim of this study was to examine the effects from wood ash on soil nutrient content, soil pH and bean growth in a farmer's field in Kisii, Kenya. A farmer survey revealed that farmers in the area generally used less fertilizer than what is recommended from agricultural authorities. Only a few used soil amendments to increase long-term soil fertility regularly. It is possible that the limited economic resources of the farmers are one explanation to these practices.

The results from the field experiment showed that wood ash increased pH in the soil, but it could not be shown to increase available nutrients. When looking at the growth of beans, there was no difference between beans that were fertilized with ash and beans that were fertilized with mineral fertilizer. That implies that wood ash can be used as a substitute for the fertilizer normally used by farmers when growing nitrogen fixing crops without lowering yields. Thus, for smallholder farmers the use of wood ash in their fields provides one tool to improve soil fertility and stop further nutrient depletion. However, there are limitations to the use of wood ash, one of them being the availability. Therefore, to ensure sustainable long-term soil fertility more than this one measure is needed.

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1 Introduction

In 2016 all member states of the United Nations agreed on seventeen sustainable development goals (Sustainabledevelopment.un.org). Reaching them is necessary to ensure that human rights are met globally, today and in the future. Goal number two aims to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture". In order to fulfil that goal, there are a number of agricultural challenges that need to be addressed. One is the issue of soil degradation. In many parts of the world, food production is limited by poor soil status. When cultivated, soils depleted of nutrients require fertilizer application to sustain plants with sufficient nutrients. Also in more fertile soils it is necessary to fertilize to prevent nutrient mining. The use of mineral fertilizer to supply these nutrients may not always be of economic benefit for the farmer. Furthermore, inappropriate use of mineral but also organic fertilizers can cause negative environmental effects such as soil acidification and eutrophication. It is therefore of great importance to use these fertilizers in an appropriate manner and also to find sustainable, affordable alternatives or complements to the use of mineral fertilizers. Another issue in degraded soils, beyond nutrient depletion, is soil acidification. One major problem occurring in acidified soils is phosphorus unavailability. The amount of plant available phosphorus can be increased if pH is raised (Kisinyo *et al.,* 2014[a]). In acidic soils plant growth can be inhibited due to toxic concentrations of Al^{3+}.

Legumes are a major source of protein in big parts of the world. In Kenya, common bean (*Phaseolus vulgaris* L.) is an important staple crop with the ability to fix nitrogen. Consequently, the need for nitrogen fertilizer is lower than for many other crops. For resource poor farmers, common bean is therefore an affordable crop that is also an important part of a nutritious diet. Furthermore, nitrogen-fixing plants have the potential to increase the amount of soil nitrogen available for the following crops in the crop rotation. Farmers in the study area report decreasing bean productivity in recent years. Possible explanations to that trend could be impaired soil fertility and insufficient weed control (Sanchez, 2002; Van Rijn, 2000) For smallholder farmers, weeding is one of the most heavy and time consuming farming activities. When off farm job opportunities compete with farm work, weeding might be one of the activities less prioritised.

Wood ash is the residue left from the combustion of wood. In many farming households in the study area wood and harvest residues are the main sources of fuel used for cooking, thus producing ash. It often has a high pH (above 7) and a relatively high content of base cations and phosphorus, even though properties are very variable. Due to the chemical composition, it has been shown that ash can be used to raise pH in soils. Its content of many of the plant nutrients often limiting plant growth suggests that wood ash could also be useful as fertilizer. However, since the content of nitrogen is low, fertilization with only wood ash would not be sufficient for most crops. In nitrogen-fixing crops however, ash might supply enough nutrients to meet the crop requirement, not only through nutrient addition but also by raising pH. An increase in pH of an acidic soil can increase availability of the nutrients already present in the soil and create a more conducive environment for the legume and its rhizobial symbionts.

In this study, the effect of ash on soil chemical parameters and productivity of *P. vulgaris* was examined and compared to the effects of mineral fertilizer and lime. The importance of the timing of weeding was also investigated.

Hypotheses to be tested were:

Ash amendment increases soil pH and adds additional nutrients to the soil as compared to recommended fertilization, farmer practice and liming.

Plant growth and bean yield is higher if fertilized with ash compared to recommended fertilization, farmer practice and liming due to additional nutrients present in ash.

Plant growth and bean yield is higher if weeding is done one week earlier than current farmer practice.

2 Literature review

2.1 Soil degradation

Smit and Smithers (1994) defines sustainable agriculture by saying that "sustainable agriculture refers to the use of resources to produce food and fibre in such a way that the natural resource base is not damaged" (from Yunlong & Smit, 1994) while current and future needs of producers as well as consumers can be met. Soils are one of the most important natural resources on which agricultural systems depend, and maintained soil fertility is a key to long-term sustainability. However, in many parts of the world including sub-Saharan Africa soil degradation is a major factor limiting agricultural productivity (Sanchez, 2002; Fageria *et al.*, 2007). Nutrient depletion and soil acidification are two processes contributing to degradation of soils.

2.1.1 Nutrient depletion

The uptake of nutrients and water by plants from soil is, together with photosynthesis, essentially the process that allows agricultural production. The nutrients are built into biomass and allocated to different parts of the plant, which of some are harvested and used for feed, fodder, fuel or other purposes. At each harvest, the nutrients taken up from the soil by the crop are removed from the field (Vitousek *et al.*, 2009). Nutrients are not only removed through plant uptake and harvest though. Other processes leading to loss of nutrients are erosion, leaching and volatilization (Henao & Baanante, 2006). If the corresponding amount of nutrients lost is not added to the soil in some form, the nutrient content of the soil will decrease. In the long run, this will lead to loss of soil fertility and productivity (Henao & Baanante, 2006; Vitousek *et al.*, 2009). This depletion of soil fertility is recognized as one of the main factors causing low food crop production in sub-Saharan Africa (Chivenge *et al.*, 2009). Macronutrients are elements that are used in high quantities by plants. These are nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) (Barker & Pilbeam, 2007). Since the uptake of these elements is high, the amount removed with harvest is often relatively big. Some of these plant nutrients, for example potassium, are made available to plants through weathering of clay minerals. However, that requires a significant content of weatherable minerals in the soil. Highly weathered soils such as Acrisols and Nitisols generally have a limited content of these minerals (Jones *et al.*, 2013).

It has been estimated that around 95 million hectares of soil in Africa are degraded to the point where big investments are needed to restore their productivity (Henao & Baanante, 2006). Nutrient losses vary between areas. Grouping three major plant nutrients (N, P and K) together Henao and Baanante (2006) estimated losses to be 9 - 88 kg NPK ha^{-1} yr^{-1} across Africa and from 40 % of the African farmland losses were higher than 60 kg NPK ha^{-1} yr^{-1}. In Kenya, total losses during the cropping seasons of 2002 – 2004 were estimated to on average 68 kg NPK ha^{-1} yr^{-1} (Henao & Baanante, 2006). An evaluation of nutrient balances in a low input corn-based farming system in western Kenya showed a negative balance for N being on average 52 kg ha^{-1} yr^{-1} (Vitousek *et al.*, 2009). For P, balance was +1 kg ha^{-1} yr^{-1}.

In a comparison between conventional and organic cropping systems in Kenya Adamtey *et al.* (2016) assessed nutrient balances in the different systems. Different levels of input were implemented in both the organic and the conventional systems. Based on common farming practices associated with each of the systems, nutrient balances for N, P and K (taken as the difference between fertilizer inputs and harvest outputs) were calculated over six years. Balances were negative or near zero for N and K in both low input systems and in the high input conventional system, but positive in the high input organic system. Balances for P were positive in all systems (Adamtey *et al.*, 2006). In contrast, P depletion of 6.6 kg P ha^{-1} yr^{-1} was reported in Rwanda, Ethiopia and Kenya (Nziguheba, 2007). Onwonga and Freyer (2006) studied nutrient balances of N, P and K at farms using traditional farming practices in Nakuru district, Kenya. They found that the balances were negative in cropping activities at all of the three study sites. For N, values ranged between -117 kg N ha^{-1} yr^{-1} to – 42 kg N ha^{-1} yr^{-1}. The corresponding values for P were – 1 kg P ha^{-1} yr^{-1} to 2 kg P ha^{-1} yr^{-1}. For K balances were – 102 kg K ha^{-1} yr^{-1} to 0 kg K ha^{-1} yr^{-1}. Nutrient balances are not only determined by the level of input to a farming system but also by other factors such as land use. When comparing different land use types, Onwonga & Freyer (2006) found the strongest negative balances in systems based on fodder, pasture and cereals. Land use types in which legumes were intercropped still showed negative balances for nitrogen in most cases (Onwonga & Freyer, 2006).

2.1.2 Soil acidification

Soil acidity can be understood as the capacity of soils to act as acids (Vorob'eva & Avdon'kin, 2006), and soil pH has a big impact on plant availability of various soil nutrients. There is no clear threshold below which a soil is defined as acid. Kochian *et al.* (2004) writes that acid soils are soils with a pH of 5.5 or lower, while McFerland *et al.* (2001) suggest that a soil is considered slightly acidic when pH is 6.5 to 6.1, moderately acid at pH 6.0 to 5.5, strongly acid between 5.0 to 5.1 and extremely acid at pH between 5.0 and 4.4. There are estimates that more than 1.5 billion ha wordwide are affected by acidification (Graham & Vance, 2003), and other approximations saying that acid soils occupy 40 % of the total global arable land (Haug & Foy, 1984). In Kenya, 13 % of the agricultural land can be classified as acidic, if defined as soil pH being lower than 7 (Kanyanjua *et al.*, 2002). Natural processes as well as anthropogenic activities cause acidification of soils. In soils formed from acidic parent material the weathering process where silicate minerals are leached will result in a natural acidification, where the base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) are lost from the soil and replaced by protons (H^{+}) and aluminium (Al^{3+}). In tropical and subtropical environments, where rainfall exceeds evapotranspiration, this process can be fairly rapid, resulting in oxides of iron and aluminium dominating the soils (Sumner & Noble, 2003; Mayer, 1998). Base saturation (BS), i.e. the proportion of cation binding sites (expressed as cation exchange capacity, CEC) on the soil particle surfaces occupied by base cations, is one parameter used to express the level of soil acidity. In agricultural systems, removal of plant material contributes to, and accelerates, soil acidification (Vieira *et al.*, 2008). Ammonium-based nitrogen fertilizers also cause acidification since the process of microbial nitrification (turning ammonium, NH_4^{+}, into nitrate, NO_3^{-}) is releasing protons (Vieira *et al.*, 2008).

Two problems to plant growth that arise with soil acidification, making the soil less fertile, is Al toxicity and P deficiency (Kochian *et al.*, 2004). Under acidic conditions, aluminium will be present in the phytotoxic form Al^{3+} in the soil solution at levels that may negatively impact plant growth (Miyasaka *et al.,* 2007; Feng Ma *et al.,* 2001). The Al toxicity inhibits root development, which reduces uptake of water and nutrients and causes poor plant growth (Kanyanjua *et al.*, 2002). It is difficult to determine a general threshold for exchangeable Al^{3+} concentration and Al^{3+} saturation above which plant growth is significantly negatively affected (Miyasaka *et al.,* 2007). Variations are big between species as well as soils. However, for many crops, a content of exchangeable Al^{3+}ions above 2.0

cmol/kg will negatively affect growth (Landon, 1984). Most maize cultivars grown in Kenya require Al^{3+} saturation on the exchange complex below 20 % (Ligeyo, 2007).

Furthermore, in acidic soils phosphates tend to form stable insoluble complexes with the dissolved Al ions making the P unavailable for plants (Bougnom *et al.,* 2001; Kisinyo *et al*., 2014[a]). This is often referred to as P fixation or sorption and highly weathered, acidic soils in the tropics may fix up to 70 – 90 % of applied inorganic fertilizers (Sanchez & Salinas, 1981). Other limitations to plant growth caused by soil acidity are e.g. deficits in K, Mg and Ca, and manganese (Mn) and iron (Fe) toxicity (Fageria & Baligar, 2008; Kisinyo *et al*., 2014[b]).

In Kenya, most acidic soils are located in western Kenya and in the highlands of the Great Rift Valley, areas with high annual rainfall and acidic non-calcareous parent materials (Kisinyo *et al.,* 2014[a]). When examining these acid soils, Kisinyo *et al*. (2014[a]) found that exchangeable Al^{3+} levels were 2.01 to 2.24 cmol/kg soil and 2.71 to 4.29 cmol/kg soil in western Kenya and Rift Valley respectively. Al saturation was 42 % to 71 % (western Kenya) and 27 % to 34 % (Rift Valley). These soils were also found to have P sorption capacities ranging from 107 mg P kg^{-1} soil (Western Kenya) to 402 mg P kg^{-1} soil (Rift Valley) (Kisinyo *et al.,* 2013). According to Kisinyo *et al.* (2014[b]) only 9.6 % to 13.5 % of P fertilizers applied to these soils are taken up by the crop.

Liming, defined as application of calcium or magnesium carbonates, hydroxides and oxides, is the most commonly used strategy to reduce soil acidity (Bougnom *et al.,* 2001; Kanyanjua *et al*., 2002). Studies conducted on acid soils in western Kenya have shown increases in soil pH and available P and lowered levels of exchangeable Al^{3+} upon liming (Kisinyo *et al.,* 2014[a]). It has been suggested that use of lime in combination with P fertilizer is of importance to manage acid soils deficient in P in Kenya (Kanyanjua *et al*., 2002; Kisinyo *et al.,* 2014[a]). However, the effect of liming is often limited to the topsoil and large quantities are needed. Furthermore, limited market access, high costs and labour intensive treatment procedures prevent many resource-poor farmers from liming (Haynes & Mokolobate, 2001; Kochian *et al*., 2004; Kisinyo *et al.,* 2014[a]).

2.2 Wood ash as soil amendment

Ash is the residue from combustion of organic materials, containing most of the inorganic nutrients and trace elements of the biomass. Fuel wood constitutes up to 61 – 86 % of the primary energy consumption in many African regions, from which ash residues are generated (Amous, 1999). In Kenya wood consumption of 6.8 kg per capita yearly has been reported (Barnes *et al*., 1984). Similar quantities were reported from South Africa by Shackleton (1993). The chemical and physical properties of ash depend on the contents of the combusted material (type of plant and which plant parts) and the burning process (e.g. temperature) but also on the conditions of collection and storage (Demeyer *et al.,* 2001; Periömäki *et al*., 2004; Pitman, 2006). However, it is a significant source of a number of plant nutrients including P, K, Mg and Ca together with a number of micronutrients (Bougnom *et al*., 2011). It also has properties resembling those of lime. Thus, applying ash to agricultural fields can compensate for nutrient losses caused by harvesting and leaching and counteract soil acidification (Saarsalmi *et al*., 2006; Nkana *et al*., 1998).

Some of the neutralising compounds present in wood ash is calcite ($CaCO_3$), fairchildite ($K_2Ca(CO_3)_2$), lime (CaO) and magnesium oxide (MgO) (Etiegni & Campbell, 1991; Ohno, 1992). The pH generally ranges from 8.9 to 13.5 (Demeyer *et al.,* 2001). Neutralising capacity of ash is often expressed as calcium carbonate ($CaCO_3$) equivalents (CCE). Etiegni and Campbell (1991) reported that hydroxides of Ca, Mg and K are the main contributors to the soluble alkalinity in ash. Due to the content of quickly soluble oxides and hydroxides, the rise in soil pH is faster after application of ash than of lime. However, the increase can last for a shorter time. Nkana *et al*. (1998) found the rise in pH to be less obvious in soils treated with wood ash than in soils treated with lime. The increase in pH was found to be larger in soils with low pH (between 4 and 5) and low content of organic matter than in soils where initial pH was higher (Ohno, 1992). As a consequence of raised pH, wood ash can contribute to lowering Al toxicity and increase available P (Demeyer *et al.,* 2001; Mbah *et al*., 2010). Additionally, wood ash can increase exchangeable base cations and ECEC (effective cation exchange capacity), as shown by Nkana *et al*. (1998).

As mentioned, a number of macronutrients are abundant in wood ash. The extent to which these are dissolved and the rate at which they are made plant available varies between elements. Oxides and hydroxides of K are normally dissolved quickly, while the dissolution of Ca and Mg depends on the dilution (faster when ash/water ratio is low) (Khanna *et al*., 1994). In acid soils, P contained in the ash may remain insoluble or become immobilized through complex formation with ions of Fe or Al (Demeyer *et al*. 2001; Bougnom *et al*., 2011). The content of N and S is low in ash, since most compounds containing these elements are almost completely oxidised and emitted as gases during incineration (Demeyer *et al.,* 2001). Despite that, plant available N may increase due to ash application, if higher pH results in higher microbial activity and increased mineralisation (Pitman, 2006). Khanna *et al.* (1994) reported increased rates of soil respiration and N mineralisation after addition of ash from eucalyptus.

Improved plant growth and yield following application of wood ash has been documented for a number of crops including *P. vulgaris* (Demeyer et al., 2001). In most cases the increase in plant growth has been connected with the nutrient content of the ash, in particular the base cations easily available for plants. Gagnon and Ziadi (2012) found improved plant P recovery in treatments with wood ash. That was thought to be an effect of reduced P sorption due to higher pH and enhanced mineralization and mobility of organic P, rather than a result of release of P from the ash (Gagnon & Ziadi, 2012). The same study reported lower yield for *P. vulgaris* in treatments with lime than in plots treated with wood ash at equal CCE applications (Gagnon & Ziadi, 2012).

2.3 Common bean (*Phaseolus vulgaris* L.)

A legume is a plant belonging in the family Leguminosae or Fabaceae. Legumes are grown for both grain and forage purposes. Grain legumes account for approximately 27 % of the primary crop production globally (Graham & Vance, 2003) and they are an important source of protein for humans as well as livestock. Common bean (*Phaseolus vulgaris* L.), pea (*Pisum sativum*), chick pea (*Cicer arietinum*) and broad bean (*Vicia faba*) are some legumes commonly grown for human consumption (Graham & Vance, 2003). Grain legumes contribute to 33 % of human dietary protein. Under subsistence conditions legume protein is of even bigger importance as protein source accounting for up to 80 % of the protein N intake (Vance *et al.*, 2000). In sub-Saharan Africa it has been estimated that common bean accounts for more than 50 % of the dietary protein requirements of households (Broughton *et al.*, 2003). Legumes have additional uses except for food and feed or fodder. For example, groundnut and soybean are important oilseed crops and other species are used as green manure crops.

The family of Leguminosae contains plant species that have the ability to fix nitrogen (N_2) from the atmosphere and turn it into NH_4^+, and can thereby increase the soil N content. This is done through symbiosis with e.g. *Rhizobium* bacteria forming nodules on the plant roots. The bacteria colonizing the roots of the legume carry out the actual N_2-fixation, giving the host plant access to easily available N compounds in exchange for carbohydrates produced by the plant. Globally, agricultural N_2-fixation accounts for some 40 to 60 million tonnes of N_2 annually (Graham & Vance, 2003). For small scale farmers with limited economic resources, growing legumes can be an important alternative input source of N decreasing the need for fertilization. However, favourable growing conditions that allow plant growth as well as N_2-fixation are required if legumes are to provide enough N to sustain the productivity of the farming system.

Due to their N fixing ability, cultivation of legumes has the potential to increase the amount of N available not only for the legume but also for following crops within the cropping system. In the tropics, two kinds of systems including legumes can be distinguished. Simultaneous systems, in which legumes are mixed with other crops, and sequential systems where legumes are part of the crop rotation. In simultaneous systems the non-leguminous species can benefit directly from contribution of N fixed by the legume, or simply by reduced competition for the available N. In sequential systems residual benefits can be provided to the crop following legume cultivation in the form of increased N inputs (Giller, 2001). Since the major part of N_2 fixed is accumulated in the legume biomass, the contribution of N to the following crop depends on the amount of crop residues that are left and decomposed in the field. Residues of legumes have a relatively low C:N ratio. As a result, they tend to be degraded rapidly with a net mineralisation of N (Palm *et al.*, 2001). Even in cases where the above-ground biomass is removed from the field there may be some contribution of N from roots and nodules. If the legumes grown are used as fodder the manure might have a higher N releasing capacity. However, that is very much dependent on the storage and handling of the manure (Giller, 2001).

Maingi *et al.* (2001) compared soil N content before and after cultivation of common bean in pure stands, maize in pure stands and beans intercropped with maize. Common beans slightly increased or maintained N content at pre-planting levels (Maingi *et al.*, 2001). Similar results were presented by Onwonga and Freyer (2006) when comparing nutrient balances of different land use types. In most cases, the balance of N was positive when legumes were cultivated as sole crop. In land use without legumes or with legume intercrops, balances were predominantly negative (Onwonga & Freyer, 2006). However, fixation of N and higher biomass production leading to increased removal of vegetative material, may lead to the pH decrease being higher in cropping systems including legumes than in systems without legumes. Vieira *et al.* (2008) found that pH decrease was about 1 unit in 19 years in legume-based cropping systems. Consequently, BS was lower and exchangeable Al^{3+} was higher in these systems than in systems without legumes.

A number of factors affect N_2 fixation rates. One component is the genetic potential of the plant and the rhizobia involved in the process. The amount of N fixed is also to a large extent restricted by environmental conditions. If plants or bacterial symbionts are stressed by temperature, water scarcity, nutrient deficiencies or chemical toxicity fixation rates will be negatively affected (Giller, 2001). Consequently, fixation rates vary greatly between different species and under different environmental conditions. N fixation has been said to be relatively weak and variable in *P. vulgaris*. Graham (1981) showed seasonal fixation rates from 3 to 125 kg N ha^{-1}. Giller *et al.* (1998) measured fixation rates of 8 – 26 kg N_2 ha^{-1} in *P. vulgaris* grown in farmers' fields in Tanzania.

In acidic soils rhizobia may not survive due to the direct effect of low pH but Al toxicity caused by soil acidity also impacts the survival of rhizobia (Graham & Vance, 2003). Even at Al^{3+} concentrations that do not affect plant growth, the initiation of nodules is reduced (Giller, 2001). Nodulation is also restricted at low soil pH due to low availability of Ca, Mg, and P (Soretire & Olayinka, 2013). Not only the bacteria needed for the N fixation can be negatively affected by soil acidity but it will also affect the plants directly. According to Baudouin (2001) common beans require a soil pH between 6.0 and 7.5 for optimal growth, although growth is possible within a pH-range of 5.0 to 8.1. Fageria and Baligar (1999) on the other hand reported a maximum yield of *P. vulgaris* at pH 5.9, observing lower yields at pH 4.9, 6.4, 6.7 and 7.0. Another study found that both shoot dry weight, grain yield and pods per plant were significantly influenced by soil acidity (Fageria *et al.*, 2013). All these parameters increased when soil pH was increased from 4.8 to 5.9 by lime application. Fageria *et al.* (2012) also found that responses to soil acidity in shoot dry weight and grain yield differed between genotypes. Tolerance against Al toxicity has been found in some cultivars of *P. vulgaris*. These cultivars exude the organic acid citrate that forms complexes with Al^{3+} to protect the plant roots (Feng *et al*., 2001).

Phaseolus vulgaris has a relatively high P requirement and is therefore sensitive to soils low in plant-available P (Boutraa, 2009). Fageria & Baligar (1999) reported maximum content of P in the bean shoot at pH 4.9 and decreasing P levels at higher soil pH. Concentrations of nutrients (P, K, Ca, Mg, Zn, Cu, Mn, Fe and B) were adequate at pH 6 (Fageria & Baligar, 1999). Kimani *et al.* (2006) state that P deficiency causes average yield losses of common bean of 250 kg ha^{-1} in East Africa. In Kisii county, where the average bean yield was 1800 kg ha^{-1} in 2016, that corresponds to 14 % (Tom Onyango George, Department of Agriculture in Kisii County, personal communication). For example, nodulation is prevented by P deficiency (Graham & Vance, 2003) and a positive effect on nitrogen fixation has been shown following P fertilization. Giller *et al.* (1998) showed an increase in both nodulation and seed yield of *P. vulgaris* when fertilized with P in farmers' fields in Tanzania. The amount of N_2 fixed increased from 2 – 8 kg N ha^{-}1 to 8 – 16 kg N ha^{-1} (Giller *et al.,* 1998). When grown under controlled conditions, application of P increased leaf area, plant dry weight, nodule biomass and P content in shoots and roots of *P. vulgaris* (Olivera *et al*., 2004).

Fixation of N is inhibited by the presence of available N in the soil. Nodule formation can be completely suppressed or reduced and the enzymatic activity of mature nodules may be inhibited (Giller, 2001). Consequently, fertilization with N can, on the contrary to P fertilization, decrease legume-rhizobial N_2-fixation rates.

N_2 fixation in *P. vulgaris* has shown to be relatively sensitive to presence of available N (Abaidoo and van Kessel, 1989). On the other hand low concentrations (1-2 mM) of nitrate (NO_3^-) can promote nodulation by enabling early and rapid root development (Giller, 2001).

2.4 Weed management

In Sub Saharan Africa, weeds are major sources of yield losses due to competition, allelopathy and parasitism. Yield reductions range from 25 % to total crop failure (Van Rijn, 2000). Weeding is a farm activity consuming a lot of farm resources in terms of time and labour (Vissoh et al., 2004). Depending on the development of the crop, competition by weeds can be of more or less significance. That means that the timing of weeding can be of great importance for crop productivity. Hall *et al*. (1992) writes that there is a critical period determining when weeding should begin and for how long the field should be kept free from weeds to avoid yield reductions due to intraspecific competition. Saito (1994) states that low returns on labour leads to smallholder farmers seeking work opportunities off farm, thus adjusting farming systems to fit the reduced labour availability. Such adjustments can for example mean limiting the area cultivated, reducing the amount of weeding or doing weeding earlier or later than what is optimal for crop productivity.

2.5 Agriculture in Kisii County, Kenya

In Kisii County in South-western Kenya, agriculture is the main livelihood strategy for 80 % of the rural population (Tom Onyango George, Department of Agriculture in Kisii County. personal communication). Creating employment and income, ensuring food security and providing raw materials to agro-based industries, the agricultural sector is central in the socio-economic development of the county (ASDSP, 2014). The sector contributes by 60 % to the county's economy (Tom Onyango George, Dep. of Agr., Kisii County, personal communication). The area is densely populated with a total population of 1.3 million and on average 935 persons per square kilometre. In the part of Kisii County where this study was conducted, Kitutu Chache South, population density is 1 348 persons per square kilometre (ASDSP, 2014). The absolute poverty rate of the county is 49.6 %. Due to high population density, the farm size is relatively small, 0.2 – 2.1 hectares (ASDSP, 2014). Out of the county area, 57 % is cultivated (Tom Onyango George, Dep. of Agr., Kisii County, personal communication). The main staple crops are maize, beans, finger millet, bananas, potatoes and local vegetables. Important cash crops are tea, coffee and sugarcane. A major part of the cultivated land is used for food crops (ASDSP, 2014).

2.5.1 Climate

Kisii County is located in a mountainous area on an altitude from 1500 to 2200 meters above sea level (Smaling *et al.*, 1993). The climate is classified as tropical rainforest climate according to the Köppen-Gelger classification (Climate-data.org). The rainfall pattern is bimodal with two rainy seasons during which crops are grown. The short rain season lasts from February to June, and the long rain season stretches from September to December. Average annual rainfall is 2070 mm (Kisii meteorological station, Figure 1). However, variation in precipitation is fairly big within the county and the average annual rainfall of the whole county is 1100 – 1750 mm (Tom Onyango George, Department of Agriculture in Kisii County). The difference in monthly rainfall was about 190 mm between the driest month (February) and the wettest (May) between 2011 and 2016 (Kisii meteorological station, Figure 1). During these years, temperatures were highest in March, the monthly average daily temperature being around 22.1 °C. The coldest month was June with an average daily temperature of 20.1 °C (Kisii meteorological station, Figure 1).

2.5.2 Soils

The soils of Kisii County are quite diverse but consist mainly of Luvic Phaeozems, Umbric Acrisols, Plinthic Acrisols and Umbric Nitisols (Jones *et al.*, 2013). Phaeozems are characterised by a thick, dark surface layer rich in organic matter. The high content of organic material and a high base saturation (>50 %) makes these soils nutrient rich and they have a good potential for agricultural production, although water holding capacity might be limited below the surface layer (Jones *et al.*, 2013; ISRIC[a]). The pH-value is normally between 5 and 7 (ISRIC[a]). Acrisols are strongly weathered, acidic soils with low cation exchange capacity (CEC) and low base saturation (ISRIC[b]). The content of Fe- and Al-oxides is high and phosphorus fixation and aluminium toxicity are limiting agricultural productivity. Therefore, if these soils are used for agriculture, there is a need for regular application of fertilizer and selection of crops tolerant to acidic conditions (Jones *et al.*, 2013). Other problems, aside from the low soil fertility, are that the soil surface of Acrisols can become very hard if left bare under dry conditions and that they are susceptible to erosion (Jones *et al.*, 2013). The third group of soils frequent in the study area are Nitisols. These soils are also strongly weathered and have a high content of iron oxides and hydroxides (Jones *et al.*, 2013). Nitisols have a high

CEC compared to other strongly weathered soils, mostly due to high content of clay and organic matter. This, in combination with a well-developed structure, make them well fit for agricultural use (ISRIC^c). Base saturation can vary from 10 % to 90 % (ISRIC^c). Phosphate fixation can be a problem in these soils due to the high content of iron oxides. Consequently, if annual crops are grown on these soils fertilizer application is a necessity (Jones *et al.*, 2013).

In the part of Kisii county where this experiment was located soil pH ranges from 4.5 to 6.19, i.e. extremely to slightly acid (NAAIAP, 2014). In 93 % of the farms sampled for the report pH was below 5.5. Therefore, non acidic fertilizers i.e. fertilizers not containing ammonium, are recommended (NAAIAP, 2014). The same report states that macro nutrients N, P, K, Ca and Mg are below adequate levels in some farms, and that in 57 % of farms sampled the micronutrient Zn was low.

2.5.3 Cultivation of common bean (*Phaseolus vulgaris* L.)

According to a household survey conducted by Agricultural Sector Development Support Programme (ASDSP) in 2014 38 % of the land in Kisii county is allocated to subsistence crops and 22.4 % is used for commercial crops. As one of the major staple crops, the area used for common bean cultivation in Kisii County was 45 100 ha in 2016 (Tom Onyango George, Dep. of Agr., Kisii County, personal communication). Common beans are planted in both the short and long rains. They are usually intercropped with maize. A majority of the households use local bean varieties, rather than planting improved seeds (ASDSP, 2014). The major nutrient inputs used by farmers in the area are basal fertilizer (used by 56 %), top-dress fertilizer (used by 33 %) and organic manure (used by 18 %). However, the survey conducted by ASDSP showed that use was below recommended levels. The biggest constraint to access inputs was reported to be high prices or insufficient income (ASDSP, 2014). Mechanisation is limited; among farming activities ploughing is the only activity during which machinery is used by a majority of the households (65 %). For that, 43 % of the farmers used plough while the remaining used oxen or other draught power animals (ASDSP, 2014).

The average bean yield for both seasons in 2016 was 1800 kg ha^{-1} (Tom Onyango George, Dep. of Agr., Kisii County, personal communication). In 2013 the average bean yield was approximately 2140 kg ha^{-1} in the long rain season, and 1240 kg ha^{-1} in the short rain season.

3 Material and methods

3.1 Study site

The experiment was established in a farmer's field located in the area of Nyakoe in Kisii County, subcounty Katutu Chache South (0°36'50.6" 34°44'30.3"E). The area receives an average annual rainfall of 2067 mm (Kisii meteorological station, Figure 1) in a bimodal pattern. Mean annual temperature is 20.8 °C (Figure 1). The field used for the experiment is a farmer's field used for annual crops, mainly maize and napier grass. The soil was a silty clay soil with pH(H_2O) 4.4, soil organic carbon content (SOC) 1.65 % and soil organic nitrogen (SON) 0.13 % (Table 2).

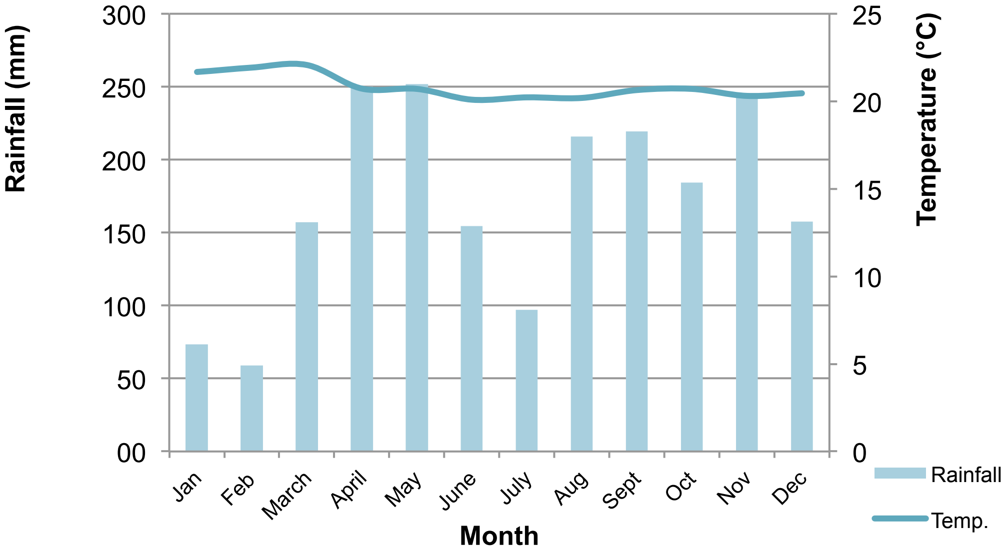

Figure 1. Average monthly temperature and rainfall 2011 - 2016 Kisii meterological station.

3.2 Experimental design and management

Two weed management treatments; W1 – early weeding and W2 – farmers practice and six fertilizer/lime treatments; Mineral fertilizer, type and dose recommended by local extension services (F2); mineral fertilizer – farmers practice (F3); mineral fertilizer – farmers practice and lime (F4); ash (F5) and lime (F6) and non-fertilized control (F1) were included in a two-factorial completely randomized block experiment with four replicates (Table 1, Appendix 1).

Table 1. Treatments of block experiment.

Factor	Treatment	Details
Weed control	W1: Early weeding	First weeding 18 - 19 days after planting (one week before farmer practice), Second weeding before flowering.
	W2: Farmers practice (i.e. average time for weeding in the area)	First weeding 25 – 26 days after planting Second weeding at pod formation.
Fertilizer	F1: Control	None
	F2: Mineral fertilizer – recommended dose	DAP*, 188 kg ha^{-1} (37.5 kg P ha-1)
	F3: Mineral fertilizer - farmers practice (FP)	DAP*, 100 kg ha^{-1} (20 kg P ha-1)
	F4: Mineral fertilizer - farmers practice (FP) + lime	DAP*, 100 kg ha^{-1} (20 kg P ha-1) $CaCO_3$, 3.8 tonnes ha^{-1}
	F5: Ash	Wood ash, 5.1 tonnes ha^{-1} (20 kg P ha-1)
	F6: Lime	$CaCO_3$, 3.8 tonnes ha^{-1}

*Diammonium phosphate; DAP-46;18;0.

Wood ash used in treatment F5 was collected from schools in the area. Before application the wood ash was ground and passed through a 2 mm sieve and thoroughly homogenized. It was analysed for organic C, N, P, Ca and M and acid neutralizing capacity (expressed as calcium carbonate equivalents, CCE) (Table 2). Ash was added to match the dose of phosphorus fertilization generally used by farmers as defined in treatment F3 (20 kg P ha-1). In treatment F4 and F6 agricultural lime in the form of finely ground $CaCO_3$ was applied in an amount that corresponded to the acid neutralizing capacity of the ash (CCE 74.3 %) added in treatment F5.

Soil preparation was carried out by hand hoeing before planting in all plots and plant residues of the preceding maize crop were removed. Plot size was 6.5 m^2 (2.4 m x 2.7 m). The net harvest plot was 1.7 m^2 (1.2 m x 1.4 m) from which 32 plants were harvested (Appendix 1). Lime and ash were applied to the plots and mixed into the top 20 cm of soil in furrows one day before planting. The Diammonium phosphate (DAP) was applied the application was done in connection with planting of the beans. Planting of beans (cv Rose Coco was done on the 2nd and 3rd of March 2017 with a spacing of 40 cm between rows and 20 cm within rows. Planting depth was 5 cm. The beans were planted approximately five centimetres next to the furrows where lime and ash had been applied. This was done to allow for the plants to access water in case of low rainfall, since the increased salt content of the soil implicated a risk of aggravating water stress under such conditions. The seeds were still placed close enough to the furrows for the roots to reach the applied nutrients. In treatments where DAP was applied planting was made in the same furrow was the fertilizer. Weeding was done at two occasions in both weeding treatments, but at different times (Table 1). Pest control was performed based on need; the field was sprayed with an insecticide (Actara) and fungicide (Ridomil) two weeks after planting. A second treatment against root rot was performed one month after planting (Ridomil). Leaves were partially removed from the plants approximately one month before harvest to accelerate the maturation of beans in accordance with local practice.

3.3 Soil and ash analysis

The field was sampled prior to experiment establishment to determine initial characteristics (Table 2). Three composite soil samples were taken at 0 - 20 cm depth using an auger. Each composite sample consisted of eight samples taken along the diagonals and a transect line across the middle of the experiment area. Samples were air-dried and passed through 2 mm and 0.5 mm sieves. The pH was measured in a 1:2.5 suspension of soil and H_2O, as well as in a 1:2.5 suspension of soil and 0.01 M $CaCl_2$ using the <0.5 mm fraction of the samples. Soil organic carbon (SOC) was determined using the Walkley-Black method (Walkley & Black, 1934) and soil organic nitrogen (SON) was analysed by the Kjeldahl method (Van Schouwenberg & Walinge, 1973) using the <0.5 mm fraction of soil. Available P was extracted by the Mehlich 1 solution (0.05 M HCl + 0.025 M H_2SO_4, Mehlich, 1953) and determined calorimetrically using a AA500 Spectrophotometer (PG instruments, UK). The content of base cations (Ca, Mg, K and Na) was determined after soil samples were leached with ammonium acetate (pH 7, Okalebo *et al.*, 2002). The leachate was analysed by flame photometry, measuring the content of the different ions at specific wavelengths. To determine the CEC the soil samples were subsequently leached with an acidified potassium chloride solution (pH 2.5; Okalebo *et al.*, 2002). Concentrations of ammonium in the leachate were measured by distillation followed by titration. All of the analyses described above were done in the <0.5 mm fraction of the samples. Soil textural class was determined on the larger fraction, 0.5 - 2 mm, using the hydrometer method (Gee & Or, 2002) where hydrogen peroxide (30 % H_2O_2) was used to remove organic matter from the samples, and Calgon consisting of 45 g Na-HMP (sodium hexametaphosphate) and 5 g $NaCO_3$ in one litre H_2O was added to the samples as dispersion agent.

Table 2. Results from analysis of ash and initial soil samples.

Parameter	**Ash**	**Soil**
Calcium carbonate equivalents (%)	74.3	N/A
pH (H_2O)	N/A	4.37
pH ($CaCl_2$)	N/A	4.09
Organic C (%)	2.45	1.65
Available P (ppm)	3900	11.1
N (%)	0.02	0.13
Exchangeable Ca	7700 (ppm)	2.9 (cmol/kg)
Exchangeable Mg	5600 (ppm)	1.55 (cmol/kg)
Exchangeable K (cmol/kg)	N/A	0.60
Exchangeable Na (cmol/kg)	N/A	0.26
CEC (cmol/kg)	N/A	13.0
Base saturation (%)	N/A	40.9

Soil samples were collected from all plots four weeks after treatments. From each plot one composite sample consisting of five soil cores, taken along the diagonals of the plot, was analysed. Sampling was done using an auger as during initial soil sampling, and samples were similarly air-dried and sieved. The characteristics determined were pH ($H_2O/CaCl_2$), SOC, available P, CEC, ECEC, available cation content and EC. Methods used were the same as described for the initial soil sampling (see above). The same methods were also used when analysing the ash for content of organic C, N and exchangeable Ca and Mg.

3.4 Plant performance data

Emergence data were collected seven days after planting by counting of all plants within the net harvest plot. Plant development was recorded by determination of the time to two development stages; third trifoliate leaf unfolded (V4), and one open flower (R1) (Fernandez & Gepts; Schwartz *et al.*, 2004). This was also done on all plants in the net harvest plot. During flowering the number of flowers were recorded at one occasion when all plots had reached development stage R1. Flowers were counted on five randomly selected plants in each net plot. Number of pods was recorded at one occasion during pod formation, also by, counting on five plants per net plot (Fernández-Luqueño *et al.*, 2010). Nodulation scoring was done six weeks after planting on four plants from each plot. The plants were taken outside the net harvest plot, two plant rows from the plot border (Appendix 1). The plants were carefully dug up using a spade, so as not to lose nodules when removing the roots from the soil. Plant vigour and colour, abundance and position of nodules were determined using a scoring scale and summarized to assess the level of overall nodulation. Three levels of nodulation are defined, based on the total score; poor nodulation (score 1 – 6), nodulation less effective (score 7 – 10) and effective nodulation (score 11 – 12) (BC Ministry of forests, 1991). Plant height was measured at the highest stem of seven randomly selected plants within the net harvest plot at two occasions. Aboveground biomass and bean grain were weighed after air-drying. Grain harvest index (GHI) was calculated according to the following equation:

$$(Grain\ yield)/(Total\ biomass\ yield) \qquad \text{(eq. 1)}$$

3.5 Farmer survey

Eleven farmers active in the surrounding area of the experiment site were asked through semi structured interviews about their farming practices when growing beans (Appendix 2). The interviews were done using an interpreter.

3.6 Statistical analysis

Statistical analysis was performed using JMP Pro 12. Prior to analysis the normality of the data was examined using descriptive statistics (scatter plot and residuals). Means for the different parameters included in the study was compared between fertilizer treatments, weeding treatments and the fertilizer×weeding interaction using Analysis of Variance (ANOVA). The null hypothesis was that there was no difference between treatments and the level of significance was set to 5 % ($p \leq 0.05$). In cases where significant differences were found, Tukey HSD test was used to examine how treatments differed. The weed occurrence was markedly low in the field throughout the experiment and the initial statistical analysis showed no impact from the different weeding approaches. Due to the general lack of weeds the hypothesis relating to weeding treatments can not be said to have been tested. Therefore, subsequent data analysis was done focusing on the fertilizer treatments across both weeding approaches. Correlations between parameters were analysed by calculation of Pearson's correlation coefficient. Similarly, the level of significance used was 5 % ($p \leq 0.05$). No effects were seen from the weeding treatments so data analysis was done with focus on the fertilizer treatments.

4 Results

4.1 Farming practices in Kisii

The farmer survey indicated that most farmers in the area have similar practices when growing beans. All respondents stated that they planted beans together with maize, but in separate rows. The climate in Kisii allows for two growing seasons per year and a majority of the farmers planted beans both seasons. Fertilizer was used at least once per year by all respondents, and in most cases every planting season. All farmers using mineral fertilizer used DAP and the average rate of application was 100 kg fertilizer ha^{-1}, corresponding to 18 kg P ha^{-1} and 46 kg N ha^{-1}. Practices were more diverse regarding use of other soil amendments. Most farmers said they add other materials with the aim to increase or maintain soil fertility occasionally, but not every season. Amendments used were farmyard manure (such as cow dung and waste from chicken and goat), compost and in a few cases ash and lime. The extent to which these amendments were used was based mainly on cost and availability. Some farmers also stated mulching as a method used to increase soil fertility.

Weeding was done manually using a hoe twice per season by a majority of the respondents. The time for the first weeding varied from two to four weeks after planting. Based on this survey, the average yield was around 560 kg ha^{-1} in stands mixed mostly with maize. Some farmers said they felt satisfied with the yield levels, while others said they were not. Two respondents stated that yields had been declining the past five years. One of these said that he believed he could do better if he had more knowledge and information about the soil status of his plot.

4.2 Soil chemical parameters

The pH ($CaCl_2$) was significantly lower in all mineral fertilizer treatments than in the ash treatment (Figure 2). The same differences could not be shown for pH (H_2O), where soil pH was lower than in the ash treatment only in the treatment receiving recommended dose of mineral fertilizer (Table 3). In the limed treatments, pH increase did not prove significant when compared to the control and fertilized plots. Base saturation on the other hand, was higher in the limed plots as well as in the ash treatment than in the control (Figure 3). Increase from the initial value was slightly more than one unit, approximately, in treatments where ash and lime was added (Table 3). The pH was higher at second sampling than the initial value in all treatments.

No differences in available P were shown between the treatments. However, average values were higher four weeks after establishment of the experiment than initially. This was recorded also in plots where no mineral fertilizer was added (Table 3). Exchangeable Ca was higher in the two treatments where lime was applied than in the control (Table 3). Exchangeable Na was higher in the ash treatment than where the recommended dose of mineral fertilizer was added (Table 3).

Table 3. Soil characteristics before (initial) and four weeks after experiment establishment. Parameters measured after treatment are presented as LSMeans (n = 8). Significant differences in bold. Letters show result from Tukey HSD test ($p \leq 0.05$). Treatments labelled with different letters are significantly different. Farmers practice is abbreviated FP.

Treatment	**pH H_2O**	**Avail. P** (ppm)	**Ca**	**Mg**	**K**	**Na**	**CEC**
			(cmol/kg)				
Initial	4.37	11.08	2.90	1.55	0.60	0.26	13.0
Control	4.75^{AB}	16.04	**2.65^{B}**	1.85	1.32	0.46^{AB}	14.0
Recommended mineral	**4.65**^{B}	25.63	3.23^{AB}	2.49	1.31	**0.32**^{B}	13.1
FP mineral	4.72^{AB}	18.44	6.26^{AB}	2.41	1.83	0.53^{AB}	13.2
FP mineral + lime	**5.51**^{A}	21.15	**5.70^{A}**	2.73	1.35	0.39^{AB}	12.7
Lime	4.86^{AB}	25.71	**5.41**^{A}	2.97	1.30	0.47^{AB}	13.1
Ash	**5.56**^{A}	26.87	4.88^{AB}	2.56	1.55	**0.54**^{A}	12.9
p-value	*0.0023*	*ns*	*0.0078*	*ns*	*ns*	*0.0261*	*ns*

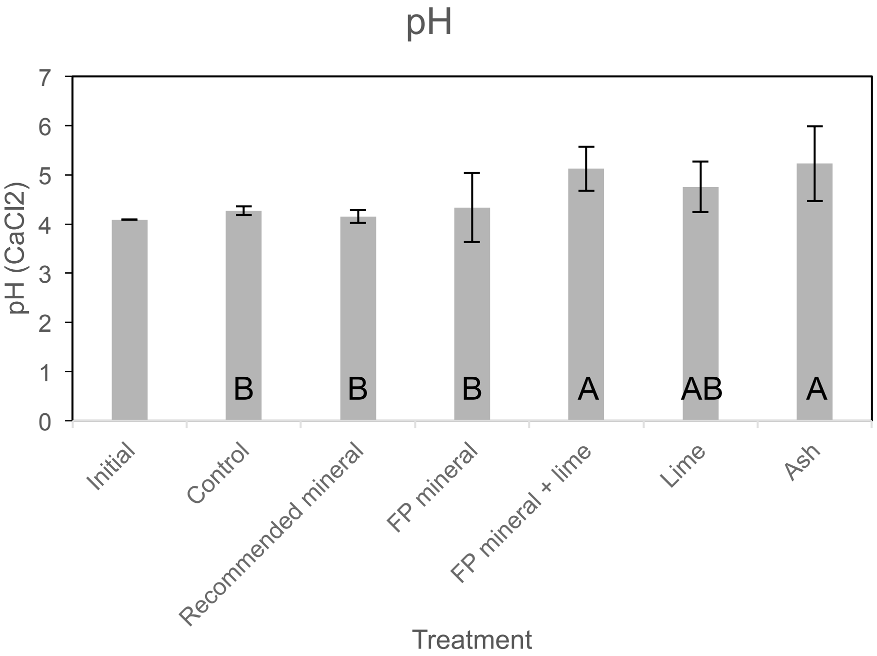

Figure 2. pH ($CaCl_2$) before (Initial) and four weeks after fertilization treatments presented as LSMeans (n = 8). Standard deviation given by the bars. Letters show result from Tukey HSD test ($p \leq 0.05$). Treatments labelled with different letters are significantly different ($p = 0.0002$).

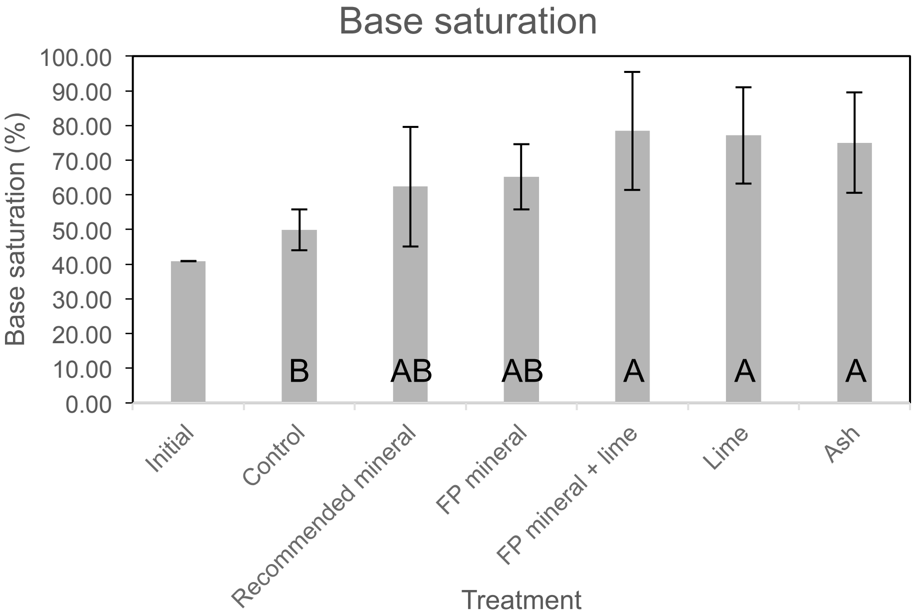

Figure 3. Base saturation before (Initial) and four weeks after fertilization treatments presented as LSMeans (n =8). Standard deviation given by the bars. Letters show result from Tukey HSD test ($p \leq 0.05$). Treatments labelled with different letters are significantly different ($p = 0.0092$).

4.3 Plant performance

There was some variation in crop vigour within the field that was not connected to treatments, based on observation. In some plots, plants were chlorotic (Figures 4 and 5) while in other parts of the field plants were vigorous. Four weeks after planting infections of root rot was found in the crop. The field was sprayed and thereafter the situation improved and the infection did not spread. Plant mortality was recorded but no correlation was found between root rot infection and fertilizer treatments. No differences in plant performance were found between weeding treatments (data not shown).

Average emergence was highest in the control, which was significantly higher than emergence in the plots that received recommended dose of mineral fertilizer and mineral fertilizer combined with lime (Table 4).Development from planting to developmental stage V4 was two days faster in plots where both mineral fertilizer and lime was added (22 days) than in plots that received only lime and the control (24 days, Table 4). However, when looking at the time from planting to developmental stage R1 there were no differences between the treatments (Table 4).

The number of flowers per plant was higher in the plots treated with ash than in the lime treatment (Figure 6). The same pattern was seen for the number of pods (Figure 7). The number of pods per plant was also higher where the recommended dose of mineral fertilizer was added, than in limed plots. Nodulation was poor in all plots (Table 4). Recorded plant biomass was lower in the lime treatment than in the treatment fertilized with the recommended dose of mineral fertilizer and the plot that received both lime and mineral fertilizer (Figure 6). There were no significant differences in the amount of bean yield between fertilizer treatments although the trend was similar to that of the plant biomass ($p = 0.0687$, Table 5). Calculation of the harvested biomass in tons ha^{-1} is shown in Table 5. Grain harvest index (GHI, eq. 1) was highest in the treatment fertilized with recommended dose of mineral fertilizer (0.54). The lowest GHI was calculated for the control (0.34). In the treatment where wood ash was applied GHI was 0.40 (Table 5). The indexes did not differ significantly between treatments.

Figure 4. Chlorotic plants at March 26th 2017. Photo:Jonna Wiklund

Figure 3. Chlorotic plants at April 10th 2017. Photo:Jonna Wiklund

Table 4. Plant performance parameters presented as LSMeans (n =8). Significantly different values in bold. Significant differences in bold. Letters show result from Tukey HSD test ($p \leq 0.05$). Treatments labelled with different letters are significantly different. Farmers practice is abbreviated FP.

Treatment	**Emergence (proportion of seeds planted)**	**Days to V4* (days from planting)**	**Days to R1** (days from planting)**	**Nodulation (total score)**	**Weed occurrence (score)**
Control	**0.90**^{A}	**24.38**^{A}	41.38	5.50	3.00^{AB}
Recommended mineral	**0.74**^{B}	24.50^{AB}	41.63	4.98	**3.25**^{A}
FP mineral	0.79^{AB}	23.88^{AB}	42.13	5.48	2.50^{ABC}
FP mineral + lime	**0.71**^{B}	**22.50**^{B}	40.88	6.01	**1.25**^{C}
Lime	0.79^{AB}	**24.25**^{A}	42.25	4.70	**1.25**^{C}
Ash	0.80^{AB}	22.75^{AB}	40.50	6.05	1.50^{BC}
p-value	*0.0008*	*0.0069*	*ns*	*ns*	*0.0004*

*Development stage V4, when the third trifoliate leaf is unfolded.

** Development stage R1, when the plant has one open flower

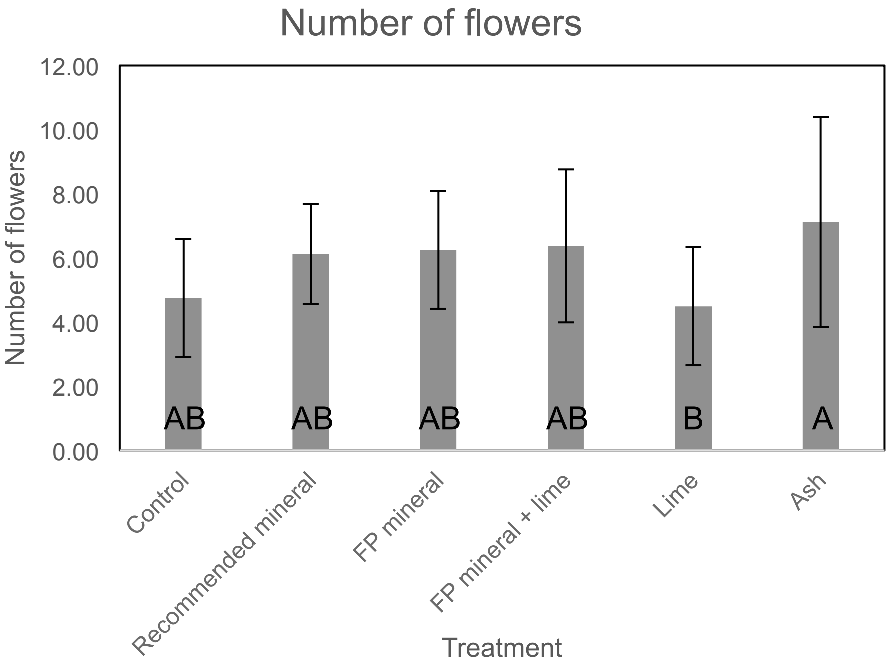

Figure 6. Number of flowers per plant in the different fertilizer treatments presented as LSMeans (n = 8). Standard deviation given by the bars. Letters show result from Tukey HSD test (p ≤ 0.05). Treatments labelled with different letters are significantly different (p = 0.0133). Farmers practice is abbreviated FP.

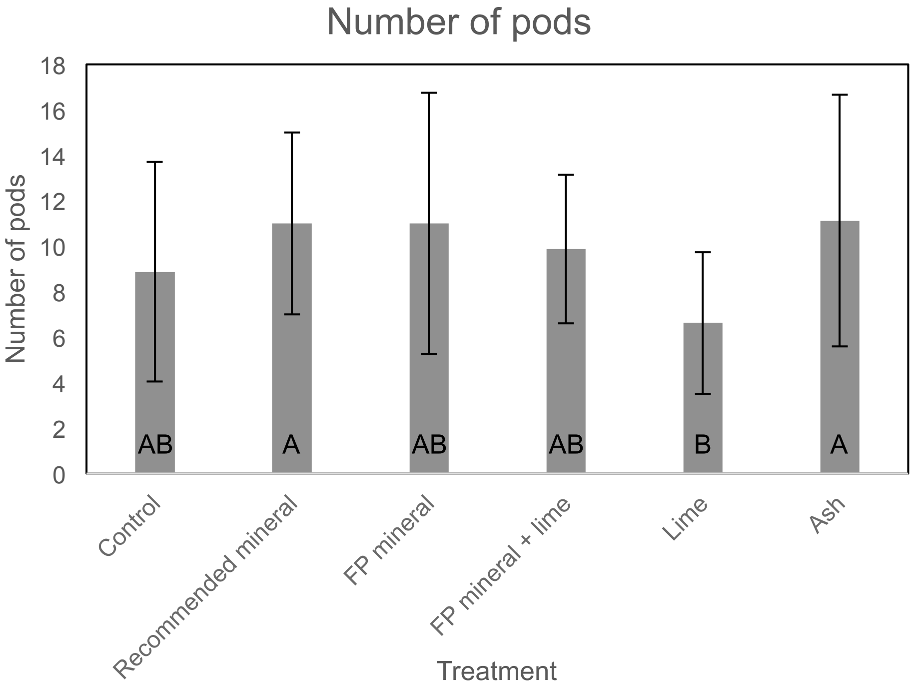

Figure 7. Number of pods per plant in the different fertilizer treatments presented as LSMeans (n = 8). Standard deviation given by the bars. Letters show result from Tukey HSD test (p ≤ 0.05). Treatments labelled with different letters are significantly different (p = 0.0088). Farmers practice is abbreviated FP.

Table 5. Harvest data given in tons ha^{-1} for the fertilizer treatments presented as LSMeans (n = 8). Significantly different values in bold. Significant differences in bold. Letters show result from Tukey HSD test (p ≤ 0.05). Treatments labelled with different letters are significantly different. Farmers practice is abbreviated FP.

Treatment	**Bean yield (tons ha^{-1})**	**Plant biomass (tons ha^{-1})**	**GHI**
Control	2.18	6.25^{AB}	0.34
Recommended mineral	2.58	**7.89^{A}**	0.54
FP mineral	3.21	7.81^{AB}	0.45
FP mineral + lime	3.30	**8.18^{A}**	0.39
Lime	1.63	**3.57^{B}**	0.52
Ash	2.90	7.44^{AB}	0.40
p-value	*0.0687*	*0.0064*	*ns*

4.4 Correlations between data

Between base saturation and pH ($CaCl_2$) an almost significant positive correlation was found (p = 0.0507, Table 6). Base saturation and CEC correlated negatively (Table 6). As could be expected, a strong positive correlation was found between the soil parameters pH (H_2O) and pH ($CaCl_2$) (Table 6).

A positive correlation found was between number of flowers and number of pods (Spearman's correlation coefficient 0.87, Table 6). Plant biomass correlated positively with both number of flowers and number of pods (Spearman's correlation coefficients 0.81 and 0.93 respectively, Table 6). The same correlation was not found between bean yield and number of flowers and pods.

When looking at correlations between soil parameters and plant performance data, some significant relationships were found. The soil pH was negatively correlated to days to V4 and days to R1. A positive correlation was shown between CEC and emergence, resulting in a higher emergence in plots with high CEC.

Table 6. Pairwise correlations between soil parameters and plant performance parameters. Spearman's correlation coefficients are given above the diagonal line and significance levels (p-values) are shown below the diagonal line. Significant correlations in bold.

	Emergence	Days to V4	Days to R1	Nr of flowers	Nr of pods	Plant biomass	Bean biomass	pH H_2O	pH $CaCl_2$	ppm P	CEC	BS
Emergence	-	0.41	0.07	-0.47	-0.24	-0.36	0.39	-0.33	-0.32	-0.50	**0.88**	-0.69
Days to V4	0.418	-	0.75	-0.69	-0.33	-0.44	0.63	**-0.96**	**-0.88**	-0.17	0.68	-0.66
Days to R1	0.890	0.086	-	-0.63	-0.45	-0.51	0.36	**-0.82**	-0.64	-0.16	0.26	-0.18
No of flowers	0.346	0.131	0.183	-	**0.87**	**0.81**	0.05	0.59	0.43	0.30	-0.63	0.34
No of pods	0.641	0.520	0.367	0.023	-	**0.93**	0.45	0.19	0.04	0.01	-0.25	-0.13
Plant biomass	0.482	0.377	0.299	0.050	0.008	-	0.22	0.27	0.01	0.17	-0.29	-0.10
Bean biomass	0.443	0.180	0.485	0.927	0.369	0.680	-	-0.70	-0.78	0.21	0.51	-0.70
pH H2O	0.527	0.003	0.045	0.220	0.716	0.602	0.120	-	**0.95**	0.36	-0.63	0.67
pH CaCl2	0.530	0.019	0.175	0.400	0.940	0.987	0.067	0.003	-	0.43	-0.67	**0.81**
Avail. P	0.308	0.745	0.756	0.559	0.989	0.749	0.695	0.528	0.395	-	-0.62	0.64
CEC	0.020	0.134	0.612	0.183	0.633	0.583	0.305	0.181	0.146	0.187	-	**-0.91**
BS	0.129	0.157	0.731	0.503	0.811	0.851	0.119	0.145	0.051	0.174	0.013	-

5 Discussion

5.1 Effects on soil chemistry from fertilizer treatments

Soil analysis after treatments showed significantly higher pH in the ash treatment when compared to treatments where mineral fertilizer was applied. In the plots treated with ash the average pH was 5.2, which is approximately one unit above the control pH (4.1) (Figure 2). From a plant growth point of view, a pH of 5.2 is preferable. This was expected, since wood ash is known to have a neutralizing effect on acid soil, (Etiegni & Campbell, 1991; Ohno, 1992; Nkana *et al.*, 1998). The same difference was not seen in treatments where lime was applied. This indicates that the increase in pH from application to soil sampling (4 weeks) was bigger after application of ash than of lime. The amount of lime added to the plots was based on the CCE of the ash, attempting to give the same neutralising capacity as in the ash treatment. However, the lime applied was in the form of finely ground $CaCO_3$, while neutralizing compounds in ash are mainly quickly soluble oxides and hydroxides of Ca, Mg and K (Etiegni & Campbell, 1991). The aim was to use quick lime in this study, so as to come as close as possible to the solubility of ash. However, the lime used was determined by market availability and thus it was not possible to use quick lime for this experiment. Etigieni and Campbell (1991) argue that the difference in solubility can lead to a faster rise in soil pH after ash application than after lime treatment which could maybe explain the differences shown between limed and ash treated plots. In this study, soil sampling was done four weeks after soil treatments. A later soil sampling could have confirmed whether this was the case, or if the difference remained longer after application.

No significant differences were seen in available P between the fertilization and liming treatments. This can be interpreted as application of ash and lime resulting in equal amounts of plant available P as if mineral fertilizer P is added. The ash used in this study had a P content of 3900 ppm and the applied ash corresponded to a fertilizer application of 20 kg P ha^{-1}. That matched the amount of P normally applied by farmers through mineral fertilizer (farmer practice). However, when wood ash is applied to acidic soils there is a risk of insolubility and immobilization (Demeyer *et al*. 2001; Bougnom *et al*., 2011). In the treatment where only lime was applied no P was added to the soil. Theoretically, a soil pH rise of one unit from the initial value (4.1, Table 1) would have the capacity to increase plant available P, which has also been shown in previous studies (Kisinyo *et al.,* 2014[a]). An increase in average soil pH was seen, although not statistically determined, in both lime and ash treatments why this could have contributed to an enhanced P supply. This study does not provide the possibility to answer whether the phosphorus available in ash treatments originated from the ash or from soil P being made plant available due to increased pH.

The lack of differences between treatments regarding base cation content was unexpected, since base cations was applied through ash but not in other treatments. The addition of wood ash has previously been shown to provide a significant amount of plant nutrients (Bougnom *et al*., 2011) and other studies have shown increased content of exchangeable base cations after ash application (Nkana *et al*., 1998). Accordingly, base saturation was expected to increase more in ash treatments compared to plots where mineral fertilizer and lime was applied. No such difference was found. On the other hand, it was expected not to find any differences in CEC, since this is mainly determined by soil properties such as texture and organic matter content.

5.2 Effect on plant performance from fertilizer treatments

Plant parameters, where differences between treatments were found, were emergence, time to specified phenological stage and number of flowers and pods per plant. Emergence (percentage of planted seeds that emerged) was higher in the control than in the plots where the recommended dose of mineral fertilizer had been applied (Table 4). It was also higher than in the plots that received both mineral fertilizer and lime. If soil salt content is too high close to the seed, this can cause water stress and consequently have a negative effect on germination and emergence. In this experiment, rainfall was low during the first three days after planting. A possible explanation to emergence being higher in the control can therefore be that the other treatments were to some extent affected by a high salt content in the soil surrounding the seeds (Okçu *et al*., 2005). Measurement of the electric conductivity of the soil after treatments could have given an indication on whether this was the case or not.

Number of days to developmental stage V4 was lowest in the treatment where both mineral fertilizer and lime was applied (significantly faster than lime and control). However, when looking at the time to the developmental stage R1, no differences were found. The importance of the difference in time between planting and V4 can therefore be questioned.

The number of flowers and pods per plant can be considered important harvest parameters since they develop into the bean seeds, which are harvested (Graham & Ranalli, 2997). The number of both flowers and pods were higher in the ash treatment than in the limed plots. One way to interpret that result is that a clearer rise in pH in the ash treatment had a positive effect on this plant performance parameter. It is also possible that the ash had other soil chemical effects that were not shown in this study, but that promoted formation of flowers and pods. There was no difference between the plots in the number of flowers and pods treated with ash and the plots where mineral fertilizer was applied, indicating that ash could work as a substitute for this fertilizer, even though this could not be detected by soil analysis.

In contrast to the formation of flowers and pods, there were no significant differences in the bean yield between treatments. This was surprising considering the importance of flowers and pods in the development of mature beans. One possible reason could be that limiting factors intervened that induced smaller grain size or fewer grains per pods in plots with higher number of pods (Graham & Ranalli, 1997). However, since the field was situated some distance from the farmstead, another potential reason could be that some beans were picked before harvest, e.g. by passers-by or by animals, contributing to the large variation between replicates. When compared to average bean yields reported in recent years (1800 kg ha^{-1} and 1240 kg ha^{-1} in 2016 and 2013 respectively) the results from this experiment are in the same range, although slightly higher in most treatments. It is not unusual to see yield levels above average in field studies. In the case of this experiment, it is possible that the weed control strategies (both early and farmers practice) were more ambitious than the strategies of most smallholder farmers in the area, resulting in generally higher yields. Furthermore, it is possible that chemical pest control was used to a higher extent than what is common practice of small-scale farmers.

The harvested plant biomass however, was lowest in the limed plots. It was significantly lower than in the plots fertilized according to recommendation or combined with lime. This effect did not follow treatment differences on soil pH, suggesting that plant growth in the field was limited not only by low pH but also by nutrient availability. A low biomass, and number of flowers and pods, in the limed plots but not in the ash-amended plots further indicates that plant growth might be limited by availability of one or more micronutrients as their plant-availability often is higher at low pH (Alloway, 2013). In the plots where ash was applied, this change might have been counteracted by the application of these nutrients. The grain harvest index (GHI) can be a useful tool to compare the relationship between bean yield and biomass production of the different fertilization treatments. The grain harvest index was highest in the treatment fertilized with recommended dose of mineral fertilizer. It is possible that the high GHI is a sign of the plants prioritising allocation of nutrients to the reproductive organs rather than vegetative. It is difficult to explain this difference with the data collected during this study. However, it would be interesting to study further in the future. When compared to average bean yields reported in recent years (1800 kg ha^{-1} and 1240 kg ha^{-1} in 2016 and 2013 respectively) the results from this experiment are in the same range, although slightly higher in most treatments. It is not unusual to see yield levels above average in field studies. In the case of this experiment, it is possible that the weed control strategies (both early and farmers practice) were more ambitious than the strategies of most smallholder farmers in the area, resulting in generally higher yields. Furthermore, it is possible that chemical pest control was used to a higher extent than what is common practice of small-scale farmers.

The chlorotic symptoms that were noticed in some parts of the field were thought to be deficiency symptoms but it could not be conclusively identified which plant nutrient that was lacking. Although the symptoms reminded of K deficiency, they were not strong enough to provide a clear diagnosis. However, if K was limited in the field, there is a possibility that K added through wood ash had an effect on the formation of flowers and pods, even though no significant difference was found in K content in the soil analysis. On the contrary, the plots where ash was added did not show a lower abundance of chlorotic plants than other plots when determined by visual examination. Another possible explanation for the chlorotic patches within the experimental area could be N deficiency. The nodulation assessment revealed generally poor nodulation in the field why the amounts of N_2 fixed from the air probably were low. However, a general N deficiency would probably have given light green or slightly chlorotic plants homogenously across the field and without mottling of the leaves. The last theory to what might have caused the symptoms is deficiency of some micronutrient. In that case, one could also expect to see less chlorotic plants in the ash treated plots, since the wood ash probably contained various micronutrients. On the other hand, as discussed above, the availability of many micronutrients is lower at high pH (Alloway, 2013). As mentioned earlier, no such differences were noted. In conclusion, the soil analysis and data of plant performance collected during the experiment does not allow determining what might be the reason for these chlorotic symptoms.

5.3 Data correlations and reliability

No strong pairwise correlations between soil data and plant performance parameters of great importance within the objectives of this study were found. It is of value commenting on the negative correlation found between BS and CEC, since this contradicts expectations. It is possible that the reason to this correlation is simply a result of inherent random errors within the statistical model, leading to false significances.

Throughout the design and layout of the experiment the aim was to enable reliable results. However, in field experiments there is always an impact from natural variation in field conditions. During the study, the crop was infected by root rot, and some plots were more affected than others. The field was sprayed when the infection was discovered but it cannot be excluded that affected the results. However, the data for plant mortality recorded did not show any signs of some treatments being more affected than others. At evaluation, possible improvements of the methods used for soil sampling were identified. To achieve more reliable results of soil parameters a larger number of samples should have been taken from each plot. Additionally, a sampling method where soil samples were consistently taken next to the row of plants along the furrow where lime and ash was placed prior to planting might have improved chances of showing differences between the treatments. Regarding data for plant performance, the counting of flowers and pods could have been done on a larger number of plants to get a more reliable data set. The lack of significant differences in plant height between treatments indicates that measurement of more plants would have been preferable.

The results presented and conclusions drawn from this experiment are limited to data from one growing season. To be able to understand long-term effects that ash might have on the soil chemistry and plant growth in Kisii, records extended over a longer period of time, for several growing seasons, are required.

5.4 Implications for smallholder farmers in Kisii

No differences between weeding treatments were found. One possible explanation to that is that the weed pressure at the field was very low (Figures 4 and 5, data not shown). This was not expected, since previous studies have found that weeds cause high yield reductions in areas similar to the study area (Van Rijn, 2000). Still, the grain yields in the experiment was above average in the area. That can be a sign of this field having an unusually low seed bank. Another possible explanation is, as mentioned, that the weed control performed in the field was improved compared to common practice, even in the farmer practice treatment. Some of the respondents of the farmer survey said that they weeded their field only once per season. That would suggest that farmers could increase yields with improved weed control, i.e. weeding twice. However, it is important to remember that weeding is also a time consuming farm activity that requires a lot of labour. Therefore, the gains of weeding twice instead of once probably have to be significant for the farmer to change the weeding strategy.

The soil analysis showed that pH could be increased using ash. Given that lime is a cost for farmers, ash of lower cost can be a vital alternative. The farmer survey conducted showed that few farmers were currently using soil amendments with the purpose of maintaining long-term soil fertility. A majority of the farmers interviewed said they were using the fertilizer DAP, containing ammonium that has an acidifying effect in the soil. Using ash as a neutralizing soil amendment on already acid soils provides an opportunity to retain and sustain soil fertility, thus avoiding a decline in yield levels. The general lack of differences in soil nutrient content and plant performance between the ash treatment and the treatments fertilized with mineral fertilizer suggests that ash could be used also to provide plant nutrients. However, using ash as a substitute for mineral fertilizer has limitations. To achieve a fertilization level of 20 kg P ha^{-1} required big amounts of ash. If the recommended level of P would have been applied to the field through ash, the amount of ash would be very large. However, such large amounts might cause problems for the farmer collecting the amount of organic material required to produce that ash and also handling and storage. Handling and storage are also pointed out as reasons to why liming is not regularly done by smallholder farmers although smaller amounts than ash are required (Haynes & Mokolobate, 2001; Kochian *et al*., 2004). Applying large amounts of ash to the field could also pose a risk of adverse concentrations of salt in the soil. To avoid negative effects in the crop, a proper application timing and technique would be of importance.

Problems with land degradation tend to be higher in areas where population density is high and land is scarce, since soils are then often intensively cultivated. As shown by the farmer survey and information given by agricultural authorities, these are the conditions in the area of Kisii. In such areas it is crucial to find sustainable ways to increase and sustain soil fertility so as to ensure food security. Therefore, and leaning on the results of this study, strategic use of ash by farmers could be of importance for crop performance and merits further investigation.

6 Conclusions

Compared to mineral fertilizer and lime, ash application lead to an increase in soil pH measured four weeks after application. No difference in nutrient status was seen between fertilizer treatments. However, the ash analysis shows that a number of plant nutrients were provided through ash application. The lack of significant differences in plant performance parameters between the ash treatment and the mineral fertilizer treatments shows that nutrients added with ash were indeed used by the crop. For some plant parameters, the treatment where only lime was added to the field were lower than the other treatments, suggesting that plant growth is first of all limited by nutrient availability and probably less by a low soil pH.

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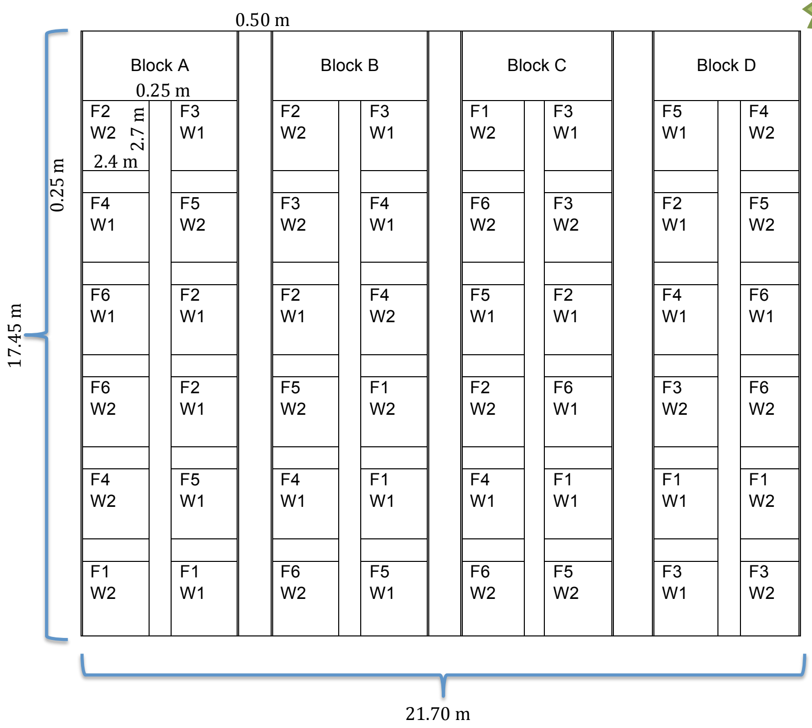
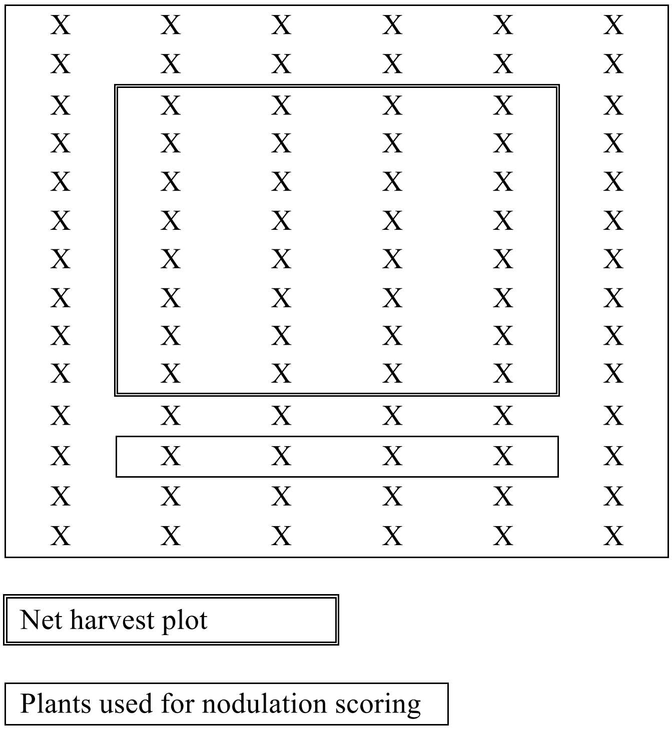
Appendix 1

Experiment layout



Factor	Treatment	Input
Weed control	W1: First weeding one week before average time for weeding in the area, second weeding before flowering.	
	W2: Farmers practice (i.e. average time for weeding in the area)	
Fertilizing	F1: Control	None
	F2: Mineral fertilizer – recommended dose	DAP, 188 kg/ha (37.5 kg P/ha)
	F3: Mineral fertilizer - farmers practice	DAP, 100 kg/ha (20 kg P/ha)
	F4: Mineral fertilizer - farmers practice + lime	DAP, 100 kg/ha (20 kg P/ha) $CaCO_3$, 3.8 tonnes/ha
	F5: Ash	Wood ash, 5.1 tonnes/ha (20 kg P/ha)
	F6: Lime	$CaCO_3$, 3.8 tonnes/ha


Net harvest plot
Plants used for nodulation scoring

Appendix 2

Questionnaire used for household survey

1. When do you plant your beans?
2. How do you plant the beans? I) in the same hole with maize, ii) in a different hoe but same row with maize iii) in a different row from tht of maize iv) not mixed with maize?
3. Do you use fertilizer when planting beans? Yes or No
4. If fertilizer is used, which one?
5. How much of the fertilizer do you use per plot?
6. Do you add anything else to increase fertility of your soil? Yes Or No
7. If yes name the other materials you add
8. If fertilizer is used, is this done every planting season? Yes or No
9. If no, how often is it done?
10. If other materials are added, is that done every planting season? Yes or No
11. If no, how often is it done?
12. How often do you plant beans on your farm?
13. When do you weed when cultivating beans?
14. How many times do you weed your bean field?
15. Which method of weeding do you use?
16. How much of the beans do you harvest from your plot?
17. Are you happy with this yield? Yes or No
18. If no, why not? Explain.