Response of *Phaseolus vulgaris* L. and *Pisum sativum* L. to N and P fertilizers and inoculation with *Rhizobium* in Kenya

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MSc Thesis PPS
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VP GROUP

WAGENINGEN UNIVERSITY
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Preface

This report was written as part of my Thesis (compulsory for study Plant Sciences at Wageningen University) performed for chair group Plant Production Systems (PPS) and carried out at Vegpro (K) Ltd., Kenya.

I was interested in this project to examine if inoculation of beans and peas with *Rhizobium* could be a feasible technique to use for a large scale production company such as Vegpro and enthusiastic about working with smallholders and testing inoculation under local conditions. Research performed under numerous conditions responses are variable, depending on combinations of factors of genotype, environment and management. Therefore, it was exciting to do field experiments and to see the effects of the various treatments in practice. Some years ago the idea of increasing reliance on biological nitrogen fixation and 'putting it to work' like intended in the N2Africa project made me really enthusiastic about the topic. I don't believe in a blanket approach and, in my opinion, the approach in the N2Africa project of identifying of niches for targeting nitrogen fixing legumes is a better way to go.

This research gives an indication that the adaptation of current management by increasing reliance on biological nitrogen fixation may lead to improved yields, and I hope that in some years it may lead to putting nitrogen fixation to work for Vegpro and its outgrowers. I am really thankful I was given the opportunity to work at such an interesting company and for all the help I received throughout my stay. I have learned a great deal because of it.

I want to thank all colleagues from Longonot and Liki outgrowers for their help and inspiring conversations. I am generally not in favour of naming people, but this research would not have been possible without the help and support of Harry, Patrick and everyone else at Longonot, John Nduru, Kirunja and others at Liki, and of course James and Johnnie. Thank you. Furthermore thanks Bruno for all the fun chats and discussions during my stay at the house.

Finally, from Wageningen University I like to thank Ken Giller for his supervision during this research, and for all the helpful, thought-provoking and pleasurable conversations and Linus Franke for being examiner of this project.

Frederik van der Bom

Executive summary

Low soil fertility and poor availability of nutrients for plants growth often hampers the production of legumes in Africa. Fertilizers can improve nutrient supply, but use by smallholders is often restricted due to high costs, lack of credit, market access etc. Alternatively, many legumes can nodulate and fix atmospheric nitrogen abundantly by the symbiotic association between the crop and soil bacteria (rhizobia). Increased reliance on this process may provide a sustainable alternative. Large scale companies, the other side of the dualistic African agriculture, have plenty of access to mineral fertilizers. However, management may still be adopted in order to make better use of biological nitrogen fixation (BNF).

Successful BNF depends on the interaction between legume genotype, rhizobial strain and environment. In some cases, for instance where native rhizobial populations are not present in the soil, inoculation may be necessary. In this study the effect of inoculation with rhizobial strains in combination with or without additional inputs of N and P was examined in common bean (*Phaseolus vulgaris* L.) and in pea (*Pisum sativum* L.). Two large trials, one in each crop, were conducted in Naivasha, Kenya, at one of the main production locations of Vegpro (K) Ltd, the largest producer and exporter of fresh produce from Kenya. A third inoculation experiment was performed on runner beans (*Phaseolus vulgaris* L.) grown on hydroponics/pumice, in order to have an indication on whether these may respond to inoculation. Finally, 18 inoculation response trials were performed on sugar snap pea, snow pea and garden pea in farmers' fields in four locations around Mt. Kenya.

Although weather affected the outcome of the trials in Naivasha, it was shown inoculation with Legumefix increased nodulation and yields of common bean. Although yields did not differ significantly (*P*=0.059), it is a clear hint that reliance on BNF can be improved. Consequently there is a need to evaluate how current management may be adjusted, because reducing N inputs could lead to substantial larger profits.

Similarly runner beans grown on hydroponics scored higher in nodulation when inoculated (*P*=0.102). Considering a negative outlier and the intensity of the growing system, caution is advised though. A replication of the current trial in unused medium is recommended to further evaluate the results of this experiment and the mediums suitability.

On average, inoculation of snow pea with Legumefix increased outgrowers' yields by a third ($P \leq 0.001$). Accordingly, outgrower profits can be raised by up to 35% by adaptation to the technology. Only one trial with sugar snap pea succeeded. In this trial the inoculated treatment did not perform better than current management, but as it is only a single observation no conclusions can be made. Similarly trials with garden pea were lost. Nevertheless the results in the snow pea trial suggest potential benefits. Therefore it is advised that more trials are to be done in the latter two crops.

1. Introduction

Kenya, like many African countries, is characterized by a dualistic nature of its agriculture: on the one hand the highly capitalised, large-scale commercial agricultural sector produces the country's top three of export products (World_Bank, 2011). On the other hand there is the smallholder sector, which is predominantly low input.

In Africa, low and declining soil fertility and poor availability of nitrogen, phosphorus, and in some cases potassium for plants growth often hampers the production of legumes (Chemining'wa et al., 2007). Fertilizers can improve nutrient supply but use by smallholders is often restricted due to high costs, lack of credit, market access etc. (Sanchez, 2002). Many legumes can nodulate and fix atmospheric nitrogen abundantly by the symbiotic association between the crop and soil bacteria (rhizobia) (Giller, 2001). Therefore, increased reliance on nitrogen fixation may provide an agronomic and economically sustainable alternative (Kaschuk et al., 2006). However, worldwide many field experiments show poor nodulation and low fixation rates (Kaschuk et al., 2006).

Successful nitrogen fixation depends on the interaction between legume genotype, rhizobium strain and environment (Giller, 2001). For instance, if soil phosphorus supply is poor, nodulation can be hindered. Inoculation with efficient strains of Rhizobium may increase yields in areas where the bacteria are not already present. A special case is common bean (*Phaseolus vulgaris* L.), which is considered promiscuous but, even though poor nodulation is often observed, often shows little response in terms of fixation rates (Giller, 2001).

1.1 VP Group

A good example of the dualistic nature of Kenyan and also African agriculture can be found in Vegpro (K) Ltd. It is the largest producer and exporter of fresh produce from Kenya as well as an expert in 'fresh cut' produce including complex added value lines such as stir fries. A wide range of quality vegetables is grown and packed all year round. Besides six private farms in Kenya, and a 1000 hectare farm situated on the East bank of the River Volta, Ghana, 1700 smallholder farmers are managed in the four major producing areas of Kenya. Legumes, specifically beans and peas, make a large portion of all the produced crops. Beans are produced on the farms in the area of Lake Naivasha but peas, that require a cooler climate, are generally produced by the outgrowers. Besides vegetables, VP Floriculture is one of the leading flower growers and exporters in Kenya and specialises in growing a wide variety of roses in five farms in Kenya. Over three million stems are produced each week. It is also the leading flower propagation business in Africa, supplying plants and other plant materials to the industry and is expanding its business to a new farm in Ethiopia which is currently under development.

The combination of working with small scale farmers as well as its own in-house production provided an opportunity to test different management strategies on multiple locations, and a possibility to determine what strategies might be practiced to make better use of biological nitrogen fixation. In this research several experiments with inoculation of common bean (*Phaseolus vulgaris* L.) and pea (*Pisum sativum* L.) were carried out at one of the production sites of Vegpro. Furthermore, 18 satellite trials were conducted at farmers' fields in four locations around Mt. Kenya, all part of Vegpro's outgrowers managing scheme.

1.2 The bigger picture

World population is expected to rise by a third to 9.1 billion in 2050 (FAO, 2009). Nearly all of this growth is expected to take place in developing countries. The fastest growth is expected in sub-Saharan Africa (SSA), where population is expected to rise by up to 114%. To feed all these mouths an estimated 70 per cent increase of food production will have to be achieved worldwide and production in the developing countries would need to almost double (FAO, 2011b). Annual cereal production will have to grow by almost a billion tonnes (from 2.1 billion tonnes today), and meat production by over 200 million tonnes to a total of 470 million tonnes in 2050 (FAO, 2009). Increasing production alone would not be enough, however. If food security in developing countries is not improved, one person in twenty - 370 million people - will still be at risk of being chronically undernourished (FAO, 2009). Therefore the challenge of feeding the world population adequately does not only mean increasing production, but also ensuring access and producing kinds of foods that are lacking to ensure nutrition security.

Currently in SSA 218 million people are undernourished (FAO, 2011a). Between 2006 and 2010 SSA received an average of 3.75 million MT of food aid deliveries per year (WFP, 2011). In theory surpluses produced by rich countries' farmers are sufficient to feed the hungry, but those in need cannot afford to buy food. Even donating would not solve the problem. 63 per cent of SSA's 841 million people lived in rural areas in 2009 (World_Bank, 2011). Most of the people in these regions depend on agriculture and a large inflow of free food would destroy their livelihood. So the way to increase food security and to diminish undernourishment is by a rise of agricultural production, faster than population growth. In developing countries over 80 per cent of this increase will have to come from intensification on existing agricultural land (FAO, 2009). Yet, those countries that need to produce more in the future are those relatively scarce in land. Worldwide, the poorest have the least access to land.

The average availability of cultivated land per capita in low-income countries is less than half that of high-income countries. Moreover the share of lands suitable for cropping is smaller (Table 1). Consequently farmers face a poverty trap of small farms with poor quality soils. Yields are generally low as a result of low inherent soil fertility, poor soil structure, inappropriate soil management practices and severe nutrient depletion. Depletion of soil fertility is a fundamental biophysical cause of low per capita food production, particularly in SSA, and has largely contributed to poverty and food insecurity (Bationo et al., 2006). Poor soil fertility is widely recognized as a major constraint, limiting smallholder farming systems (Conway and Toenniessen, 2003, FAO, 2012, Smaling et al., 1997, Bekunda et al., 1997).

Table 1 Share of world cultivated land suitable for cropping under appropriate production systems (From FAO, 2011b).

				Rain fed crops (%)		
Regions	**Cultivated land (Mha)**	**Population (mln)**	**Cultivated land per capita (ha)**	**Prime land**	**Good land**	**Marginal land**
Low-income	441	2651	0.17	28	50	22
Middle-income	735	3223	0.23	27	55	18
High-income	380	1031	0.37	32	50	19
Total	1556	6905	0.23	29	52	19

Until halfway of the previous century shifting cultivation was widely practiced throughout SSA. Lands covered by bush or forest were cleared and cultivated until yields declined, after which farmers moved and repeated the same process in another location. This allowed the exhausted land to rebuild fertility through long periods of fallow (Giller and Palm, 2004). From about 1980, with increase of population this practice became unfeasible, particularly in the eastern African region (Okalebo et al., 2006). For illustration, between 1979 and 2009 the population of the southern part of the Rift Valley Province of Kenya increased from roughly 1.8 million to almost 5.4 million (Jaetzold et al., 2010). Practices have shifted to more continuous systems, putting large pressure on the lands. Technologies and farming systems typically in use are low management, low input and more intensive forms of soil fertility management are regularly not practiced (Bekunda et al., 2002). As a result crop yields are well below potential (Table 2). For almost all crops and in all regions, yield gaps in African smallholder farming are among the largest in the world (Tittonell, 2012).

Table 2 A comparison of potential (research station) and on-farm yields of selected staple and cash crops grown in East Africa (From Bekunda et al., 2002).

Crop	Potential yield (t/ha)	On-farm yield (t/ha)		
		Uganda	Kenya	Tanzania
Banana *	40 - 60	5.7	-	6.4
Maize	5 - 7	1.6	1.8	-
Beans	2.5	0.8	-	0.6
Cassava	50	8.5	-	-
Coffee *	2	0.5	2.9	0.4

* yields per year

The decline of production and soil nutrient reserves is visible across all African sub regions. Two thirds of the lands are estimated to be degraded (Bationo et al., 2006). It is especially prominent in Ethiopia, Kenya, Malawi, and Rwanda, attributed to extensive hillside cultivation. Annual nutrient depletion rates in East Africa are estimated at 41 kg nitrogen (N), 4 kg phosphorus (P) and 31 kg potassium (K) per hectare (Sanchez et al., 1997). Figure 1 shows nitrogen balances for 6 cropping systems in three districts in Kenya. All crops, including the cash crops (tea and coffee) that are allocated more nitrogen fertilizer inputs, show a negative balance. At continental scale nutrient losses are equivalent to 1,400 kg/ha of urea, 375 kg/ha of triple superphosphate (TSP) and 896 kg/ha of KCl every year, a value of U.S.$ 4 billion in fertilizer (Sanchez, 2002). Nutrient depletion may be overcome by the use of these mineral fertilizers but, unfortunately, often these do not come at a price the majority of smallholder farmers in SSA are able to afford or, moreover, farmers do not have access to them.

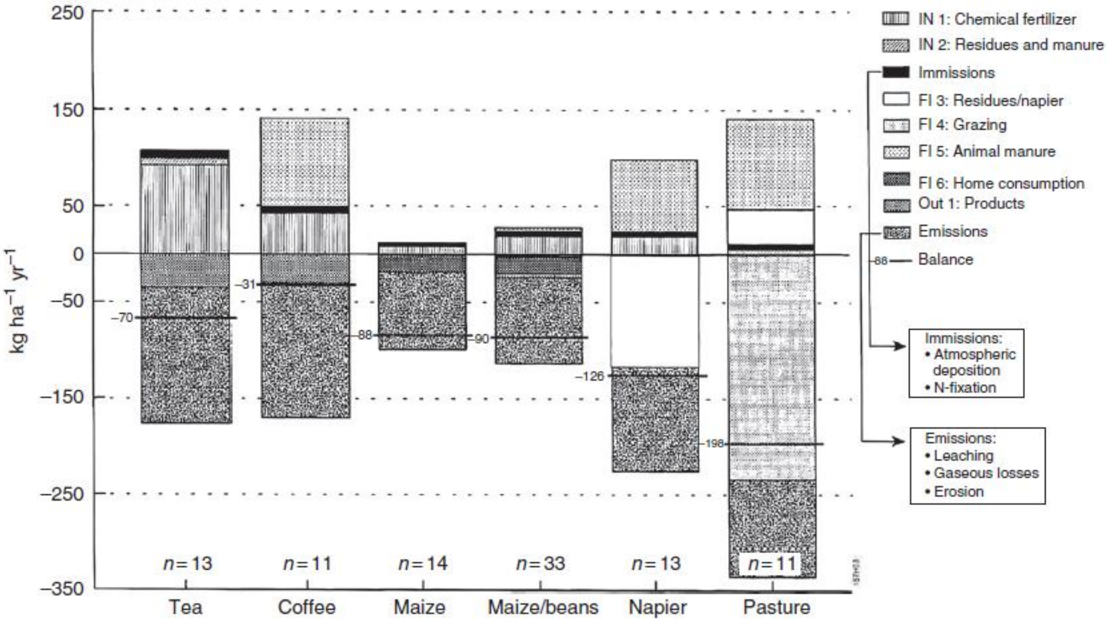


Figure 1 Nitrogen flows and balances for six crop systems in East Africa. Number of field observations are denoted by n (From Bekunda et al., 2002)

Farm-gate fertilizer prices in SSA are among the highest in the world, many times more than in Europe, North America or Asia. In 2002 the price of one metric ton of urea is about U.S. $90 in Europe, $120 delivered in the ports of Mombasa, Kenya, or Beira, Mozambique, $400 in Western Kenya (700 km from Mombasa), $500 in Eastern Uganda and $770 in Malawi (transported from Beira) (Sanchez, 2002). Part of these large differences can be explained by poor infrastructure. It costs about $100 to move 1 ton of fertilizer 1,000 km in SSA (Bationo et al., 2006). By contrast, transporting the same amount over 1000 km in the United States costs only $15, and $30 in India. Other reasons are transaction costs, removal of subsidies, inadequate access to foreign exchange and credit facilities, poor market development and lack of knowledge. Consequently fertilizer use in SSA has remained stagnant over the last 40 years, at around 9 kg ha−1 (Gilbert, 2012). Conversely, Asia, where the use of mineral fertilizers has been widely adopted since the green revolution, uses 96 kg of fertilizer per hectare of cultivated land. Yields have increased to averages of 2.5 t ha^{-1} and 4.5 t ha^{-1} in South Asia and East Asia respectively (Gilbert, 2012).

1.3 Legumes

Sustainable solutions are needed to solve the problems that smallholders face in SSA. These need to be compatible with local socio-economic conditions. A solution often promoted to increase productivity of cereal-based cropping systems in developing countries is the intensification of legume production (plants belonging to the family *Leguminosae* or *Fabaceae*). Grain legumes are often valued as being the "meat for the poor" because of their high protein content and the low prices of pulses compared with meat. Beans for instance are a major staple food crop throughout SSA and thought to be the second most important source of dietary protein (Kaizzi et al., 2012). They complement other foods such as maize, a prime source of carbohydrates, by which they play an essential role in human nutrition. On top of that they are rich in minerals such as iron and zinc (Table 3). Thus, consumption of a combination of cereals and legumes (in the ratio of 2:1) will ensure a balanced diet. Growing legumes may also be an opportunity to improve income and livelihoods by the marketing of produce. Moreover, many legumes can capture atmospheric nitrogen (N_2) by a process called Biological nitrogen fixation (BNF). They do so by forming a symbiosis with soil-borne N_2 fixing bacteria of a range of genera including *Azorhizobium, Bradyrhizobium, Mesorhizobium, Rhizobium or Sinorhizobium* (Giller, 2001). The process takes place in a specialized organ on the roots, and in some cases on the stems of the plant, called the nodule. In essence the bacteriod is supplied with energy by the plant, and it provides nitrogen in the reduced form of ammonium (NH_4^+) in return (Giller, 2001). By a mechanism called sink stimulation this process results in an increase of the rate of photosynthesis, more than the C costs of the rhizobial symbioses (Kaschuk et al., 2009). Accordingly, it improves photosynthetic nutrient use efficiency and the proportion of seed yield in relation to the total plant biomass (harvest index) (Kaschuk et al., 2009). Thus legumes can take advantage of nitrogen supply from rhizobia without compromising the total amount of photosynthates available for plant growth.

Nodulated legumes have the potential to fulfil their demand for nitrogen by fixation and, as a result, can influence the nitrogen balance of the soil (Hardarson and Atkins, 2003). In Africa they seasonally fix between 15 and 210 kg N ha^{-1} (Bekunda et al., 2010). Growing legumes may increase availability of nitrogen to accompanying or succeeding crops. When effectively recycled net soil N accrual of recycled legume residue can be as much as 140 kg ha^{-1} (Giller, 2001). Given this unique capacity and the soil fertility issues described earlier legumes could play a vital role in sustainable soil management. Mugabe (1994) estimated that by taking advantage of BNF 50% of the fertilizer needs of most of the marginal lands of Kenya, Zimbabwe and Tanzania could be fulfilled. Thus, expenditures on fertilizer imports could be largely reduced. Legumes could play a pronounced role in ensuring sustainable, low cost production by smallholders in SSA. However, even though they have the potential to fix nitrogen, legumes do not necessarily contribute to improving soil fertility. In many cases legumes can be net N-extractors by removing a larger proportion of nitrogen from the soil than contributing by fixation (Giller and Cadisch, 1995) and net nitrogen contribution can be negative if nitrogen rich parts are removed from the system by harvesting. Furthermore, if residues of grain legumes are not incorporated in the field immediately after harvest they tend to become net extractors as accumulated nitrogen disappears over the dry season (Giller and Cadisch, 1995, Franke et al., 2008). Finally, legumes often simply do not reach their full production potentials. Successful nitrogen fixation depends on the interaction between legume genotype, rhizobial strain and environment.

Table 3 Mineral contribution of beans assuming 15 kg per capita annual consumption (From Broughton et al., 2003).

Nutrient	Content of average daily serving (125g cooked)	Adult male requirement (mg)	% Adult requirement in one serving
Sodium	0 mg	2200	0
Potassium	475 mg	3900	12
Calcium	65 mg	800	8
Phosphorus	161 mg	800	20
Magnesium	56 mg	350	16
Iron	2.78 mg	10	27
Zinc	1.24 mg	15	8
Copper	0.307 mg	2.5	12
Manganese	0.668 mg	3.75	18
Selenium	0.002 mg	0.05 - 0.2	1 4
Iodine	0.032 mg	150	0
Starch	2.21 g	570 g (2750 kcal.)	4
Protein	8.5 g	69 g	12

1.4 Limitations to BNF

The main environmental constraints to nitrogen fixation in the tropics include limitations of water, nutrients and toxicities (Giller, 2001). Particularly if soil phosphorus supply is poor, nodulation can be hindered. Table 4 provides an overview of factors limiting nodulation and BNF. One major environmental factor that influences the performance of the symbioses is the availability of nitrogen in the soil. BNF is driven by the plants demand for nitrogen, which can be acquired from the soil, as fertilizer or by nitrogen fixation. With adequate levels of soil- or fertilizer-N (application levels above 25kg N ha^{-1} or more) BNF is suppressed (Bekunda et al., 2010). However, 'starter' nitrogen rates of as little as 5–10 kg N ha^{-1} may promote early growth and nodulation resulting in greater amounts of nitrogen fixation, and eventually yields (Hardarson and Atkins, 2003). Furthermore, variability within the indigenous populations of *Rhizobium* can play a very large part in whether BNF will make a contribution at all. Similarly depending on promiscuity a legume may nodulate with a wide variety of rhizobial strains, or not. Proper management in managing these aspects is therefore of great importance. Inoculation of legumes with species-specific *Rhizobium* may increase the success of their establishment, root nodulation, biomass and biomass nitrogen yields. This may be necessary where (Bekunda et al., 2010):

1. compatible native rhizobia are lacking;
2. current population compatible rhizobia is insufficient to initiate rapid population;
3. indigenous populations of *rhizobium* are ineffective or less effective than elite inoculants strains.

1.5 Other benefits of BNF

In addition to the benefits described in Section 1.3 three other advantages can be thought of when considering BNF:

1. Synchronised N supply with the plants demand;
2. Reduction of nutrient loading into the environment;
3. Reduced carbon footprint.

The latter is related to the production of N fertilizers. This takes place via utilization of the Haber–Bosch process, in which synthetic ammonia is directly produced from hydrogen and nitrogen. This process requires high temperatures and pressures and, as a result, consumes tremendous amounts of energy. Hence, when relying on N fixation rather than on fertilizers, energy consumption will be largely reduced.

Table 4 Factors limiting nodulation and/or biological nitrogen fixation (Based on Giller, 2001).

Factor	Effect
High soil temperature	Reduces the survival of rhizobia in soil and inhibits nodulation and fixation
Soil moisture	Reduces rhizobial numbers, limits migration of rhizobia, reduces nodulation and N2-fixation
Soil acidity	Reduces the survival of rhizobia in soil, inhibits nodulation and N2-fixation and leads to P fixation. Increases aluminium toxicity and calcium deficiency
P deficiency	Inhibits nodulation, N2-fixation and rhizobial growth
Salt stress	Reduces nodule formation, respiration and nitrogenous activity
High soil N level	Inhibits root infection, nodule development & nitrogenous activity
Herbicides, fungicides and insecticides	Inhibits rhizobial growth; reduces nodulation and N2-fixation; deforms root hairs and inhibits plant growth
Competition from native organisms	Suppression of inoculation by native rhizobia
Micronutrients	
Boron	Reduction in number and size of nodules
Cobalt	Reduction and delay in nodule initiation, reduced multiplication of rhizobia in the plant, N deficiency
Copper	Reduced N2-fixation
Iron	Reduction in nodule initiation, nodule development and N2-fixation rate
Molybdenum	Ineffective nodules, N deficiency
Nickel	Nodulation delayed, plant growth reduced
Selenium	Reduced hydrogenase activity and autotrophic growth in free-living *Bradyrhizobium*
Zinc	Reduction in number and size of nodules

1.6 Economics of inoculation

A great advantage of rhizobial inoculation is that it is much cheaper than mineral nitrogen fertilizer. According to Odame (1997) field trials in Kabete and Embu showed Rhizobium strains fix more nitrogen as compared to applying a recommended 90 kg of mineral nitrogen fertilizer per ha of common beans. From this comparison; the price of KShs 295 for a 100 g packet of Biofix (a form of Rhizobium inoculant sufficient to inoculate 15 kg of common bean or pea seed); and the price of 100 kg of inorganic CAN (Calcium Ammonium Nitrate) fertilizer at KShs 4341 follows that inoculation may be up to 15 times cheaper than commercially produced nitrogen fertilizers. Moreover, a 100g packet of Biofix is also lighter to transport and requires less labour for application.

Ndakidemi *et al*. (2011) evaluated the yield and economic benefits of legume inoculation under farmer conditions in two districts in northern Tanzania. It was indicated that (1) (brady)rhizobial technology was just as efficient as inorganic-N fertilizers in supplying N to common bean and soybean respectively; (2) given the high costs of mineral fertilizers, “no doubt” inoculation was a better option for resource-poor farmers who cannot afford to purchase expensive inputs; (3) combined use of P fertilizers and rhizobial inoculants can further increase grain yield; and (4) increased grain yield and profits per hectare, relative to unfertilized plots, by use of N and P alone were smaller than those using inoculation technology. However, Kipkoech *et al.* (2007) showed that in western Kenya, even though it increased yields of groundnut (1,36 t/ha vs. control 1,2 t/ha) rhizobial technology did not perform better than DAP (1,8 t/ha) or NPK (1,65 t/ha). Benefit cost ratios determined in this study were, in order of magnitude: DAP 3.0:1, NPK 2.8:1, inoculation 2.5:1, control 2.4:1, indicating highest profitability of DAP. It is worth noting that groundnut is considered a promiscuous legume however.

1.7 Objectives

The use of legumes is a promising option of increasing yields, profits and nutrition for smallholders in SSA, especially in areas where soil nutrient availability is low. Success however depends on various climatic and edaphic factors as well as the status of native rhizobia in the soil. Inoculation might be necessary to overcome the latter constraint. A simple field trial can indicate whether inoculation might be beneficial on a specific location. In the case of a resource poor farmer income may be increased without the need of large investments. Or inoculation may replace the use of mineral N fertilizer for farmers with larger endowments. Depending on local conditions the BCR for an inoculated crop could be larger than for a fully fertilized one even if attained yields would not reach up to the same level. In this study the effect of inoculation with rhizobial strains in combination with or without additional inputs such as phosphorus was examined in common bean (*Phaseolus vulgaris* L.) and in pea (*Pisum sativum* L.). A large fertilizer and inoculation trial in each of the crops was conducted at one of Vegpro's main production locations in Naivasha, Kenya and a total of 18 inoculation response trials were performed in farmers' fields in four locations around Mt. Kenya; Maritati, Kisima (Meru District), Kirima and Rongai (Nyeri District). All farmers were part of Vegpro's Liki River Outgrowers managing scheme, in which local farmer grow cash crops (Garden pea, snow pea and sugar snaps) that are eventually sold in Europe. Goals were:

1. To evaluate current nutrient management practices;
2. To determine whether reliance on biological nitrogen fixation can be increased.

Furthermore an experiment was performed on runner beans (*Phaseolus vulgaris* L.) grown on hydroponics/pumice in order to have an indication whether these may respond to inoculation.

1.8 Report outline

In this report two main activities are described: i) field trials in Naivasha and ii) outgrower trials around Mount Kenya. In section 2 the study areas are described, after which Section 3 further explains the experiments conducted at each location. Section 4 presents the results for both activities, which will be further discussed in Section 5. Finally, conclusions and recommendations are given in Section 6.

2. Description of the study sites

The experiments were conducted in two Vegpro divisions: (1) Vegpro (K) Ltd, Farming division, Longonot horticulture farm, located in Naivasha, which is the main vegetable producing area and (2) Vegpro (K) Ltd Liki River Outgrowers, one of the local farmer management schemes, based in Nanyuki. Experiments in the latter division took place at farmers' fields in Maritati, Kisima (Meru District), Kirima and Rongai (Nyeri District) (Figure 2).

Figure 2 Map of Kenya with the locations of the experimental sites indicated by each label.

2.1 Longonot horticulture farm

Longonot horticulture farm is located south of Lake Naivasha (0°50'S, 36°22'E) at an altitude of 1940 m above sea level. Average annual rainfall is 685 mm with a bimodal character in distribution, where the first rainy season, the long rains come between April and the beginning of September and the second rainy season, the short rains, from the end of August to the begin of December (Figure 3). Water from the lake is used for irrigation purposes.

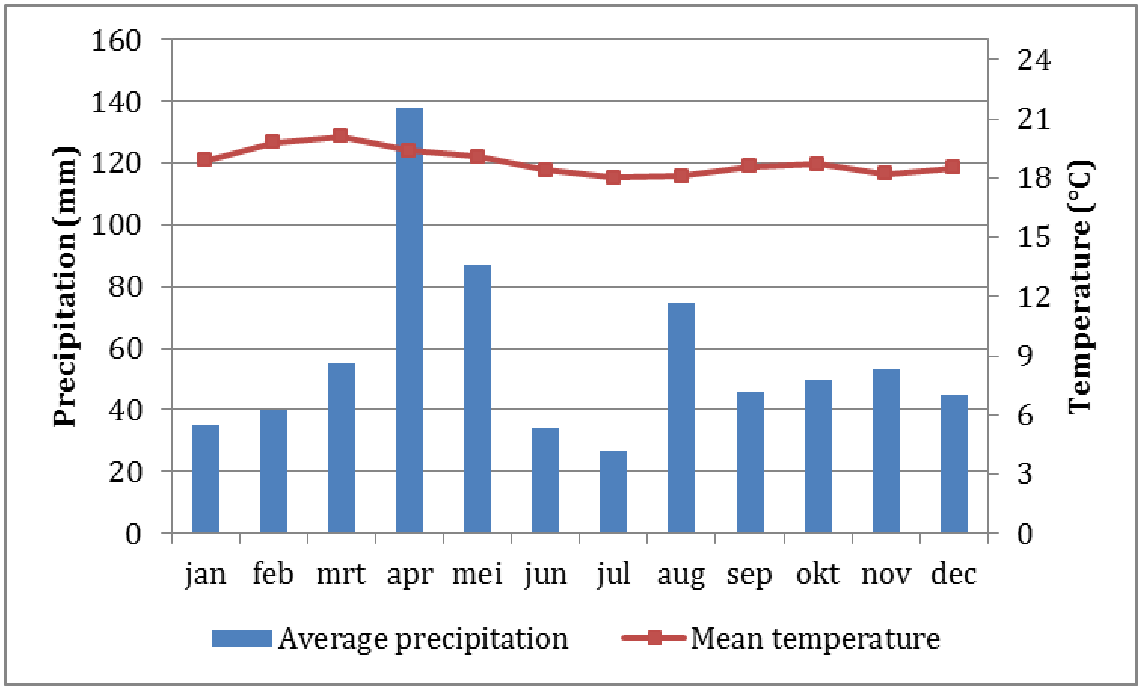


Figure 3 15 year average precipitation and mean temperature for Longonot horticulture farm, Naivasha (Based on data from Jaetzold et al., 2010)

According to the classification made by Jaetzold (2010) Longonot is partially located within the Livestock-Sorghum Zone (UM5) with a (weak) very short to short cropping season (+vs/s) and a (weak) very uncertain second rainy season (+vu) and partially in the Lower highland Ranching Zone (LH5) (Figure 4). The UM5 zone has a good yield potential for crops if farm management and water conservation has highest standard. LH5 lands are marginal. Soil type is classified as type P1PC, complex of: well drained, moderately deep to deep, dark brown, friable and slightly smeary, fine gravelly, sandy clay loam to sandy clay, with a humic topsoil: ando-haplic phazoems and: imperfectly drained, moderately deep to deep, strong brown, mottled, firm and brittle, sandy clay to clay: gleyic cambisols, fragipan phase; and PvP1, excessively drained to well drained, very deep, dark greyish brown to olive grey, stratified, calcareous, loose fine sand to very friable sandy loam or silt: ando-calcaric regosols.

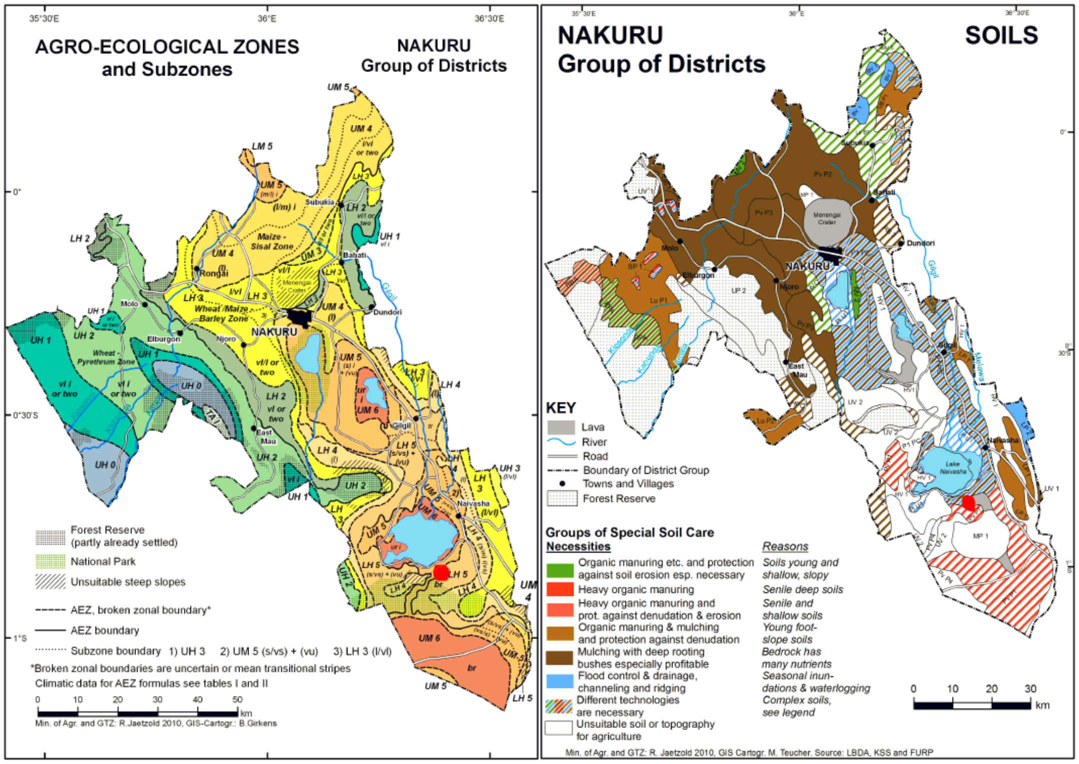


Figure 4 Agro ecological zones and soils of the Nakuru group of districts with the location of Longonot horticulture farm, marked red (From Jaetzold et al., 2010).

2.2 Liki River Outgrowers

2.2.1 Kirima/Rongai

Kirima (Coordinates 0°13'S, 37°00'E) and Rongai (Coordinates 0°14'S, 37°00'E) are situated in Nyeri district. With 197 persons per km^2 in the year 1999, Nyeri is the second least densely populated district in Central Province. Nevertheless, agricultural land available per household has decreased from 1.80 ha in 1979 to 1.60 ha in 1999, as a result of population growth (Jaetzold et al., 2010). Economic livelihood is dependent on agriculture. Over 67% of the total area is arable land. The main agro-ecological zones are UM2 (Main Coffee Zone), LH4 (Cattle - Sheep – Barley Zone) and LH5 (Ranching Zone) (Figure 5). In all divisions except in the semi-arid Kieni E. and W., available agricultural land per household is less than 0.88 ha, while that per person is only 0.22 ha or in some cases even as little as 0.15 ha . Kirima inhabits a total of 4,191 people in 1,059 households (104 persons per km^2).

Nyeri district holds about 188,800 ha of potential agricultural land. The main income is generated by three export cash crops: tea, of which planting is still slowly increasing, coffee and pyrethrum. Tea production reached 6,400 ha in 2003, yielding almost 11,100 kg/ha of green leaves each year. Coffee is cultivated on about 12,000 ha, yielding 330 kg/ha per year and pyrethrum production yields about 95 tons per year. Coffee and pyrethrum yields have been decreasing for many years as a result of low prices and high costs of inputs.

Experiments were conducted within a 2km radius from Kirima and Rongai. Altitude ranges between 1890 - 1980m above sea level and annual mean temperature between 16.9 - 15.6 °C. Average rainfall in this area is 700-800 mm per year with the first rainy season between April and the beginning of September and the second rainy season from the end of October to the end of December. They are located in the agro ecological zones of LH4, with a (weak) short to medium cropping season, and (weak) very short intermediate rains, and in LH5, with bimodal rainfall and intermediate rains (Figure 5). Soil type is LB3: well drained, moderately deep to deep, dark brown, friable to firm, clay loam to clay, predominantly with a thick humic topsoil: Ortho-luvic Phazoems; with chromic Luvisols (Figure 5).

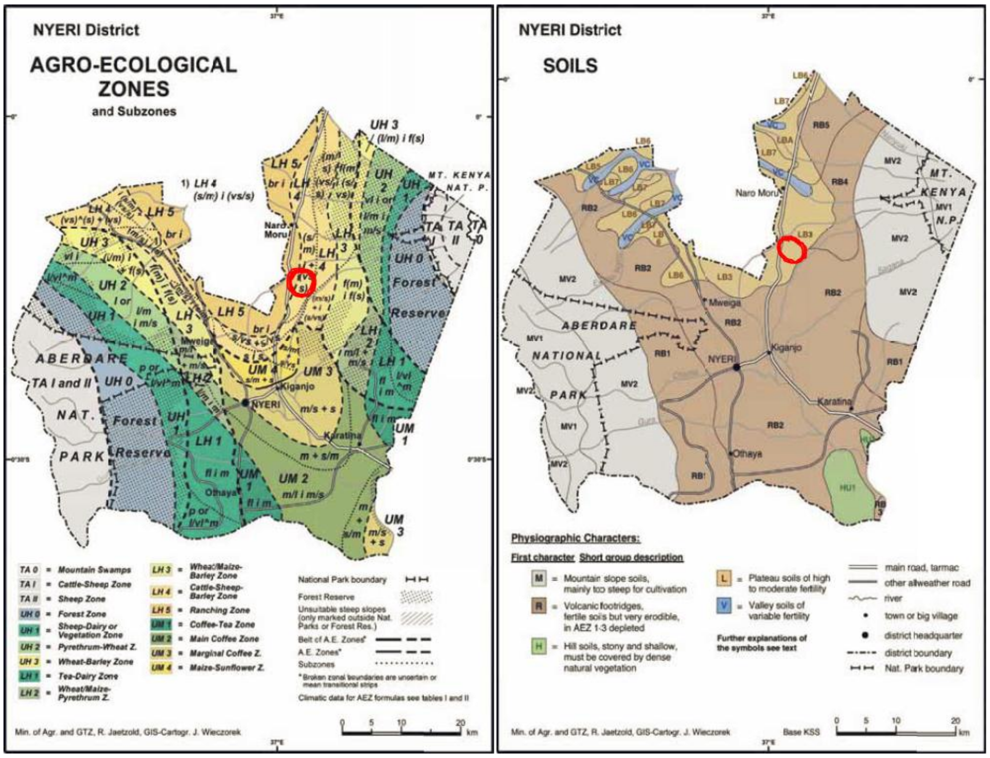


Figure 5 Agro ecological zones and soils of Nyeri district with the experimental locations' area encircled with red (From Jaetzold et al., 2010).

2.2.2 Maritati/Kisima

Experiments were done in a 2 km radius from Maritati (Coordinates 0°05'N, 37°19'E), elevation 2500m above sea level and Kisima (Coordinates 0°07'N, 37°24'E), elevation 2400 m above sea level. These are located in the Timau area of Meru Central district, on the northern side of Mt. Kenya. Annual mean temperature ranges between 15.8 - 10.5 °C. This side of the mountain is typically known for the large scale growing wheat and barley (zone UH3, Figure 6). Rainfall, 700-800 mm annually, follows a bimodal pattern with a 1st rainy season, starting mid-March and a 2nd rainy season, starting mid Oct. As a result of the rain shadow of the mountain and the effects of the western Kenya rainfall pattern can be very scattered however.

Soil type is classified as RB5 (Figure 6): well drained, moderately deep to deep, dark reddish brown, friable to firm clay; with a humic topsoil – chromo-luvic phazoems; in places very deep and overlying buried eutric nitisols. The volcanic soils round the mountain are naturally rich in fertility. Nevertheless, continuous cultivation without any returns has caused an increasing depletion of nutrients. This problem is exacerbated in the lower parts by the fact that acid granites and gneisses are the basement and nutrient content is naturally low.

During the last Population and Housing Census of 1999, Meru Central had a total population of 498,880. 253,755 Individuals (38,775 households) lived below poverty line. Timau Division, encompassing 22.8 % of the district's size, houses 9.8 % of the population (72 persons/km^2). However, Timau hosts large-scale dairy and wheat farms of an average size of 680 ha so only 0.34 ha of land was available per resident. By 2009 this would have further decreased to only 0.22 ha. Maritati houses 1632 households (41 persons/km^2) of an average of 2.71 person/family. Kisima houses 3942 (37 persons/km^2) with an average of 3.73 person/family.

Rain fed agriculture in Meru Central is limited to 168,000 ha of land. Outputs are among the highest in Kenya. Many smallholders grow tea on a total of 3,000 ha, yielding 8,900 kg of green leaves per ha per annum. Coffee covers 18,620 ha yielding roughly 16,412 kg of clean coffee per annum. Like in Nyeri district productivity has been declining since 1999. The situation is similar for pyrethrum since 1996.

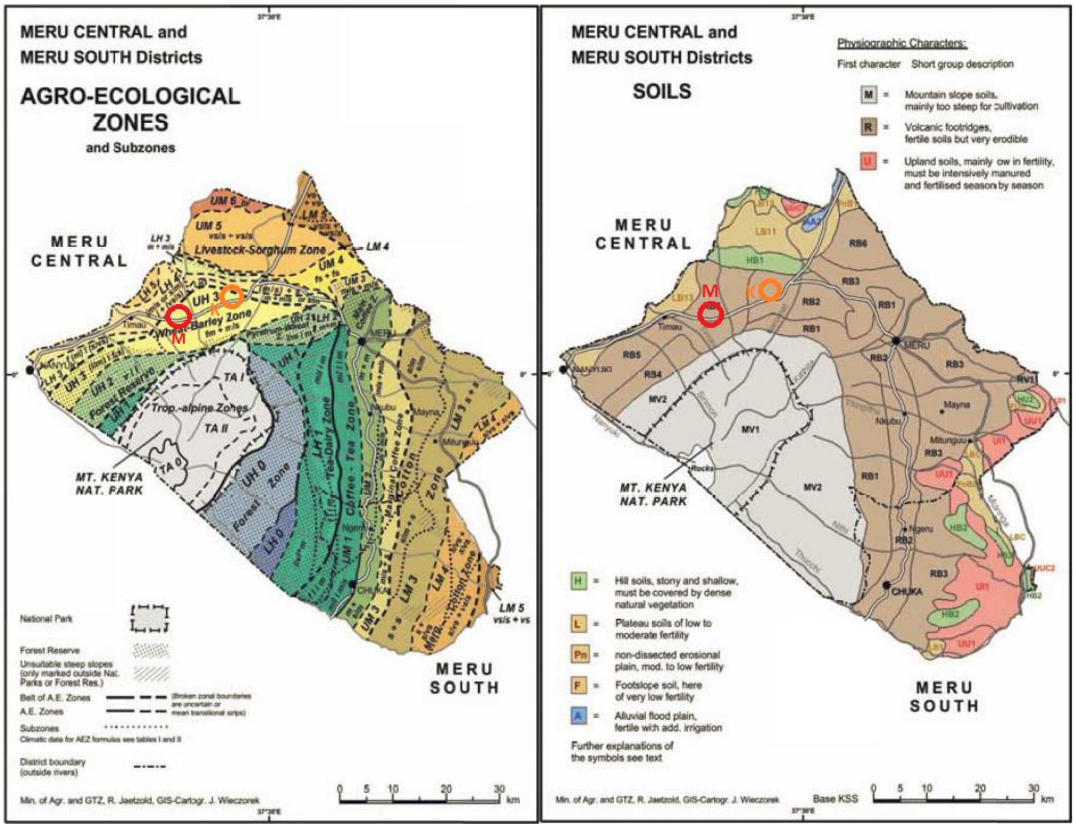


Figure 6 Agro ecological zones and soils of the Meru Central and Meru South districts with the experimental locations' area encircled with red (Maritati, M) and Orange (Kisima, K) (From Jaetzold et al., 2010).

3. Materials and methods

3.1 Longonot Experiments

3.1.1 Field experiments

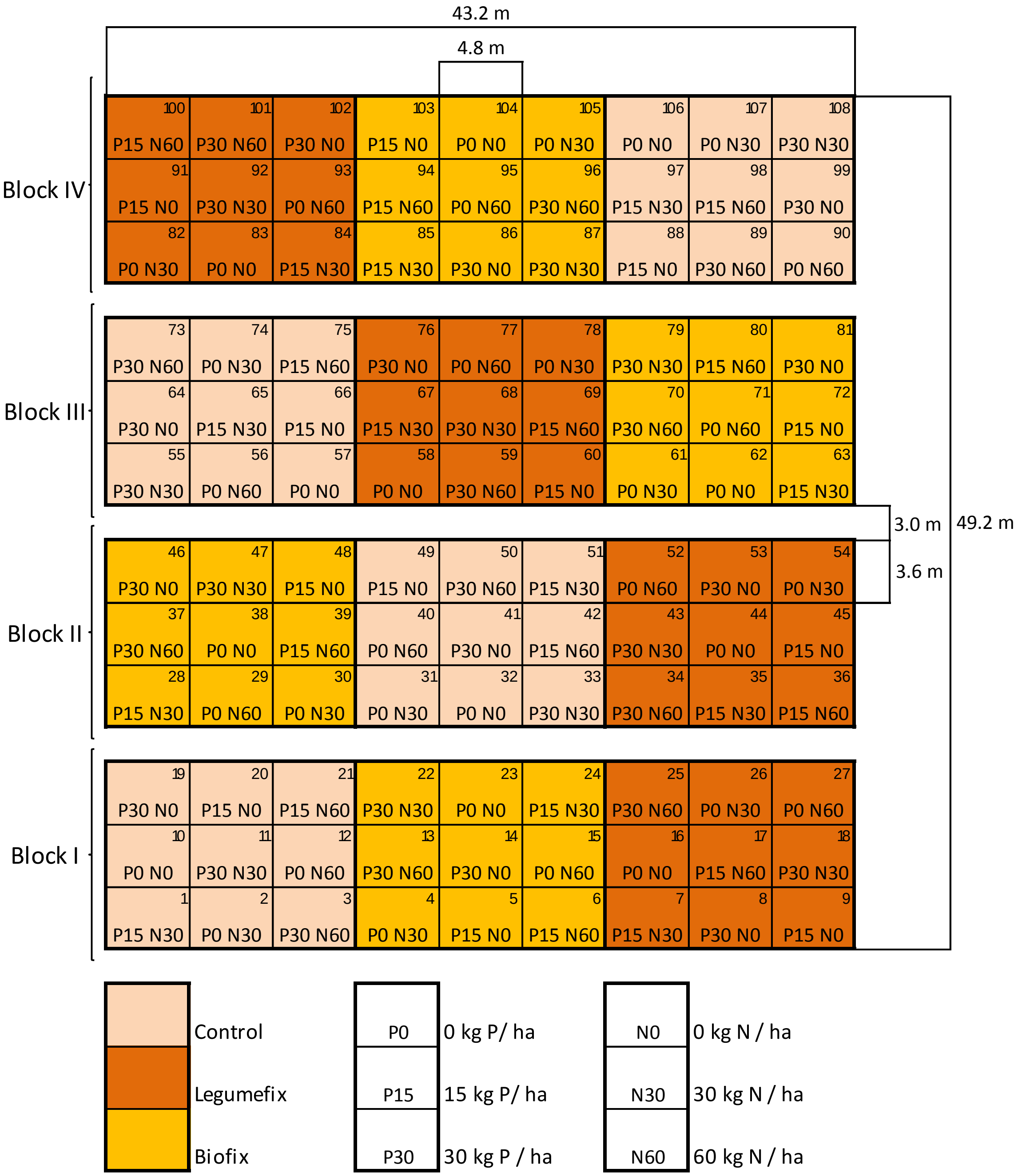
Experimental description

Field experiments were carried out between April and August 2012. A field was chosen that had not been cropped for 7 years. Soil samples were taken from 0-20cm depth by Crop Nutrition Laboratory Services on march 29 and analysed for pH, phosphorus, potassium, calcium, manganese, magnesium, sulphur, copper, boron, zinc, potassium, iron, aluminium, cat ion exchange capacity, EC (salts), Organic Matter, nitrogen, and percentage sand, silt and clay (Table 5) by the methods described in section 3.4. Climatic data was collected from the farm weather station (Appendix I).

Table 5 soil characteristics of the experimental site at Longonot.

pH	OM	N	P	Ca	Mg	K	Na	C.E.C	EC	Mn	S	Cu	B	Zn	Fe	Al	Sand	Silt	Clay
	%	%	mg/kg	cmol/kg					uS/ cm	mg/kg							%		
6.96	2.02	0.078	109.0	4.4	1.4	1.5	0.3	8	112	37	9.00	1.15	0.31	12.45	206	498	82.2	7.28	10.5

The experiments were laid out in a randomized complete block design with a split plot arrangement and replicated four times (Figure 7 - 9). Between the blocks an alley was left for a tractor to pass. Two similar trials were conducted, one with common bean (*Phaseolus vulgaris* L. cv Serengeti) and one with garden pea (*Pisum sativum* L. cv Sommerwood). The varieties were selected based on their use in the company. The common bean trial was planted on April 23rd, spaced 0.60 m inter-row and 0.055 m intra-row resulting in a planting density of approximately 300,000 plants per ha. Garden pea was planted on May 17th on beds spaced 1.00 m centre to centre with two rows on each bed spaced 0.10 m between rows and 0.03 m between seeds.



Block IV

100 P15 N60	101 P30 N60	102 P30 N0	103 P15 N0	104 P0 N0	105 P0 N30	106 P0 N0	107 P0 N30	108 P30 N30
91 P15 N0	92 P30 N30	93 P0 N60	94 P15 N60	95 P0 N60	96 P30 N60	97 P15 N30	98 P15 N60	99 P30 N0
82 P0 N30	83 P0 N0	84 P15 N30	85 P15 N30	86 P30 N0	87 P30 N30	88 P15 N0	89 P30 N60	90 P0 N60

Block III

73 P30 N60	74 P0 N30	75 P15 N60	76 P30 N0	77 P0 N60	78 P0 N30	79 P30 N30	80 P15 N60	81 P30 N0
64 P30 N0	65 P15 N30	66 P15 N0	67 P15 N30	68 P30 N30	69 P15 N60	70 P30 N60	71 P0 N60	72 P15 N0
55 P30 N30	56 P0 N60	57 P0 N0	58 P0 N0	59 P30 N60	60 P15 N0	61 P0 N30	62 P0 N0	63 P15 N30

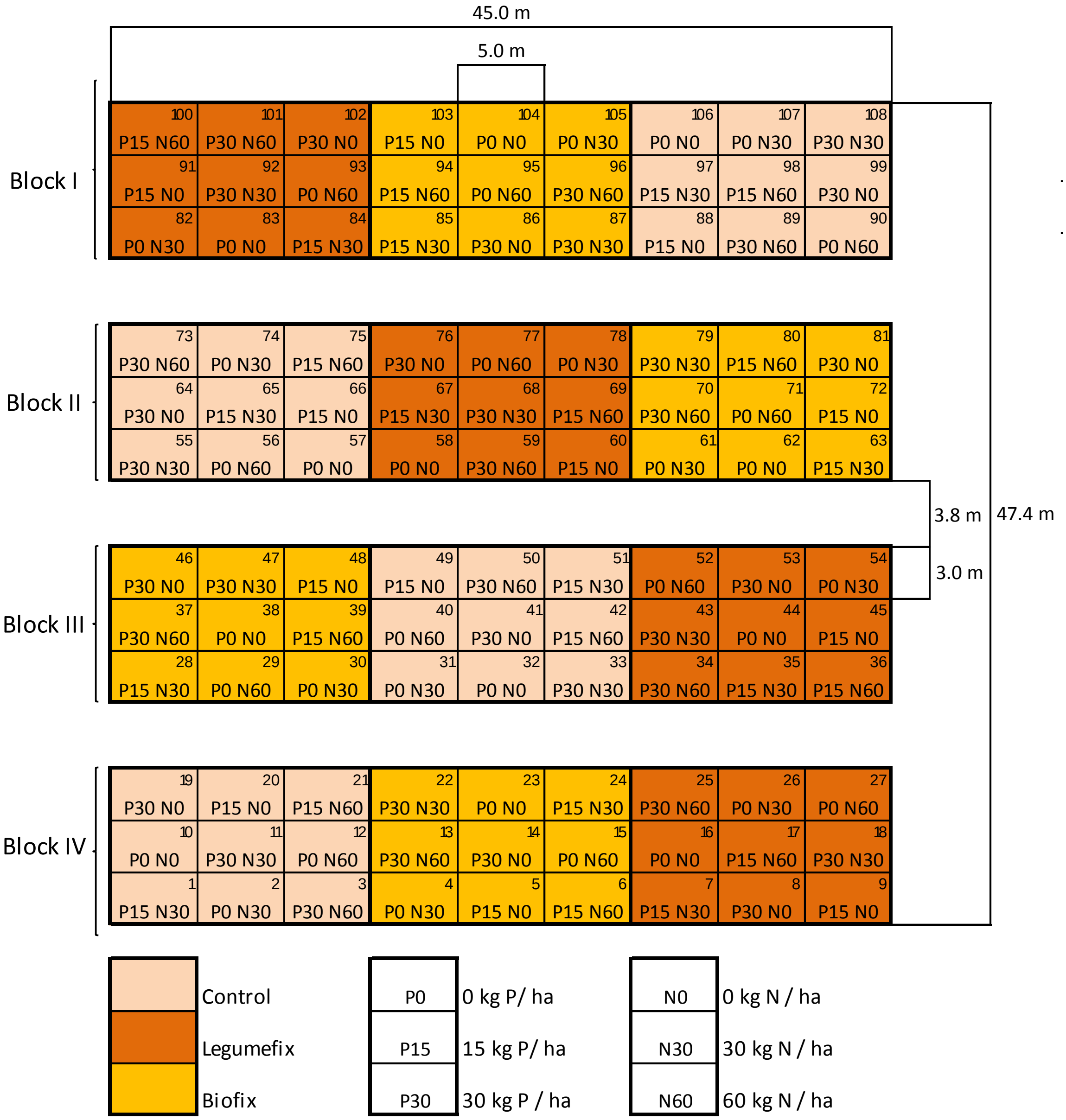
Block II

46 P30 N0	47 P30 N30	48 P15 N0	49 P15 N0	50 P30 N60	51 P15 N30	52 P0 N60	53 P30 N0	54 P0 N30
37 P30 N60	38 P0 N0	39 P15 N60	40 P0 N60	41 P30 N0	42 P15 N60	43 P30 N30	44 P0 N0	45 P15 N0
28 P15 N30	29 P0 N60	30 P0 N30	31 P0 N30	32 P0 N0	33 P30 N30	34 P30 N60	35 P15 N30	36 P15 N60

Block I

19 P30 N0	20 P15 N0	21 P15 N60	22 P30 N30	23 P0 N0	24 P15 N30	25 P30 N60	26 P0 N30	27 P0 N60
10 P0 N0	11 P30 N30	12 P0 N60	13 P30 N60	14 P30 N0	15 P0 N60	16 P0 N0	17 P15 N60	18 P30 N30
1 P15 N30	2 P0 N30	3 P30 N60	4 P0 N30	5 P15 N0	6 P15 N60	7 P15 N30	8 P30 N0	9 P15 N0

Figure 7 Layout of the bean experiment. The experiment was laid out in a split-plot design, subplots as full factorials. Whole plot treatments were a control; inoculation with Legumefix (rate 400g for 100 kg of seed); and inoculation with Biofix (rate 100g for 15 kg of seed). Subplots were a combination of three factors of P fertilization in the form of TSP (0 kg/ha, 15 kg/ha and 30 kg/ha) and three factors of N fertilization in the form of urea (0 kg/ha, 30 kg/ha and 60 kg/ha). The experiment was replicated four times, creating a total of n=108 plots. Each block (replication) was separated by a 3 m alley. The trial was planted on April 23rd, spaced 0.60 m inter-row and 0.055 m intra-row..



Block I

100 P15 N60	101 P30 N60	102 P30 N0	103 P15 N0	104 P0 N0	105 P0 N30	106 P0 N0	107 P0 N30	108 P30 N30
91 P15 N0	92 P30 N30	93 P0 N60	94 P15 N60	95 P0 N60	96 P30 N60	97 P15 N30	98 P15 N60	99 P30 N0
82 P0 N30	83 P0 N0	84 P15 N30	85 P15 N30	86 P30 N0	87 P30 N30	88 P15 N0	89 P30 N60	90 P0 N60

Block II

73 P30 N60	74 P0 N30	75 P15 N60	76 P30 N0	77 P0 N60	78 P0 N30	79 P30 N30	80 P15 N60	81 P30 N0
64 P30 N0	65 P15 N30	66 P15 N0	67 P15 N30	68 P30 N30	69 P15 N60	70 P30 N60	71 P0 N60	72 P15 N0
55 P30 N30	56 P0 N60	57 P0 N0	58 P0 N0	59 P30 N60	60 P15 N0	61 P0 N30	62 P0 N0	63 P15 N30

Block III

46 P30 N0	47 P30 N30	48 P15 N0	49 P15 N0	50 P30 N60	51 P15 N30	52 P0 N60	53 P30 N0	54 P0 N30
37 P30 N60	38 P0 N0	39 P15 N60	40 P0 N60	41 P30 N0	42 P15 N60	43 P30 N30	44 P0 N0	45 P15 N0
28 P15 N30	29 P0 N60	30 P0 N30	31 P0 N30	32 P0 N0	33 P30 N30	34 P30 N60	35 P15 N30	36 P15 N60

Block IV

19 P30 N0	20 P15 N0	21 P15 N60	22 P30 N30	23 P0 N0	24 P15 N30	25 P30 N60	26 P0 N30	27 P0 N60
10 P0 N0	11 P30 N30	12 P0 N60	13 P30 N60	14 P30 N0	15 P0 N60	16 P0 N0	17 P15 N60	18 P30 N30
1 P15 N30	2 P0 N30	3 P30 N60	4 P0 N30	5 P15 N0	6 P15 N60	7 P15 N30	8 P30 N0	9 P15 N0

Figure 8 Layout of the pea experiment. The experiment was laid out in a split-plot design, subplots as full factorials. Whole plot treatments included a control; inoculation with Legumefix (rate 400g for 100 kg of seed); and inoculation with Biofix (rate 100g for 15 kg of seed). Subplots were a combination of three factors of P fertilization in the form of TSP (0 kg/ha, 15 kg/ha and 30 kg/ha) and three factors of N fertilization in the form of urea (0 kg/ha, 30 kg/ha and 60 kg/ha). The experiment was replicated four times, creating a total of n=108 plots. Each block (replication) was separated by a 3.8 m alley. The trial was planted on May 17th with three beds per plot, spaced 1.00 m centre to centre and with two rows on each bed spaced 0.10 m between rows and 0.03 m between seeds.

Two inoculant treatments, Legumefix and Biofix, and a control formed the main plots. The subplots were a combination of three levels of nitrogen (0, 30, 60 kg ha^{-1}) and three levels of phosphorus (0, 15, 30 kg ha^{-1}). Phosphorus was supplied in the form of Triple Super Phosphate (TSP; 45% P2O5), nitrogen in the form of urea (46% N). Other management was consistent across all plots.

Figure 9 The pea trial (left) and the bean trial (right) as performed in the field

In the case of Biofix inoculation was at the rate of 6.7 g per kg of seed. The seeds were wetted with tap water and gum Arabic sticker that was supplied with the product and then thoroughly mixed with the inoculant in the shade and sown immediately to prevent excessive drying which reduces the viability of the inocula. In the case of Legumefix inoculation rate was 4.0 g per kg of seed. Here too the seeds were thoroughly mixed with the inoculant in the shade and sown immediately. As Legumefix uses a polymer adhesive no gum Arabic sticker is needed. Care was taken to avoid cross contamination of uninoculated seeds and plots with rhizobia, by planting the uninoculated seeds before the inoculated seeds and to avoid cross contamination of the two inocula, by having separate people handling each product. The most experienced and accurate planters in the company were selected to minimize variability caused by the latter procedure.

Nodule assessment

When all plants were well established nodulation was scored and recorded for each plot, based on the system devised for soybean described in Peoples *et al.*(1989) (Figure 10). The system devised for soybean presented in figure 10 represents an adaptation of the classification criteria used by Corbin *et al.* (1977) when visually ranking nodulation in field-grown chickpea and should be regarded as a guide only; it was reconsidered and calibrated in the field for each of the two experiments.

Six plants were randomly selected from a 0.50 m x 1.80 m quadrat, excluding the outer rows, and dug up in such a way that the root system and nodules are recovered. The scores from all plants were added and then divided by 6 to obtain a mean nodule score. A mean nodule score of: 4 - 5 represents excellent nodulation; excellent potential for nitrogen fixation 3 - 4 represents good nodulation; good potential for fixation 2 - 3 represents fair nodulation; nitrogen fixation may not be sufficient to supply the N demand of the crop. 0 - 2 represents poor nodulation, little or no nitrogen fixation.

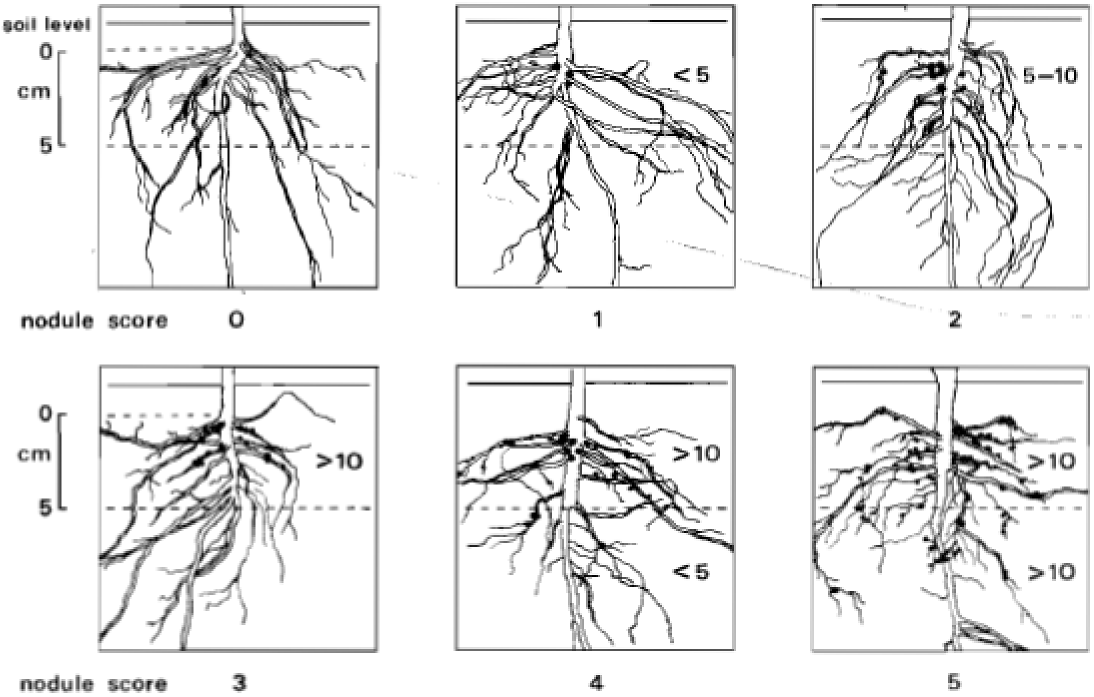


Figure 10 Diagrammatic representation of the visual classification criteria used to evaluate the root system of soybean. Nodule score is judged by the number of effective nodules in the crown-root zone (regarded as the region 5 cm below the first lateral roots) and elsewhere on the root system (From Peoples et al., 1989).

Yield and biomass production

At maturity, pods were harvested from each experimental plot, excluding the border rows, nodule scoring quadrat and 0.50 m edges. Fresh weight and number of harvested plants were recorded. In the case of the common bean trial all plots were sampled by harvesting all plants including the roots within each plot, excluding the border area. Biomass was immediately weighed in the field to determine fresh weight.

Nitrogen content and calculations

Ten common bean plants were randomly selected from the plants sampled for fresh weight determination and sent to the laboratory for nitrogen concentration analysis (by the method specified in Section 3.3) and used for quantification of total plant N. By assuming the dry weight content of a bean plant equal to 33.7% (measured) and taking the average fresh weights, dry matter concentration was calculated by:

$$\text{Dry matter concentration (DMC)} = 0.337 \times \text{Fresh biomass} \qquad \text{(eq. 1)}$$

Total plant N was then calculated for each plot by:

$$\text{Total plant N} = \text{Fresh biomass} \times \text{DMC} \times \text{N concentration} \qquad \text{(eq 2.)}$$

3.1.2 Hydroponic runner beans inoculation trial

As part of their agricultural practices Longonot has a unique system in which runner beans (*Phaseolus vulgaris* L. cv White Emergo) are grown in hydroponics (Figure 11). To test whether these may respond to inoculation a one hectare field was selected with pumice that had been used two previous cropping seasons. Simultaneously another trial testing the use of calcium cyanamide (Perkla®, CaCN2), a slow release fertilizer with fungicidal properties, was tested at the same site as an effort to suppress *F. oxysporum*. This location was chosen because it was the only block available within the research' timeframe.

Figure 11 Beans grown on hydroponics.

The area was divided into 64 rows, with each row consisting of two 49m long troughs. Half of the area was treated pre-planting with 250 kg/ha of calcium cyanamide with the boundary located in the centre of the field. The other half was subject to 500kg/ha of calcium cyanamide. The 32 centre rows were selected and separated into plots of four adjacent troughs; 8 plots for each of the calcium cyanamide treatments. Half of the plots were randomly selected and inoculated with Rhizobium (Legumefix at the rate of 400g for 100 kg of seed). The troughs were planted with two rows of runner beans, cv. 'White Emergo', spaced at 20 cm row to row and 17 cm within (Figure 12). Six plants were randomly selected from each plot and evaluated for root nodulation in a similar way as described in Section 3.1.1.

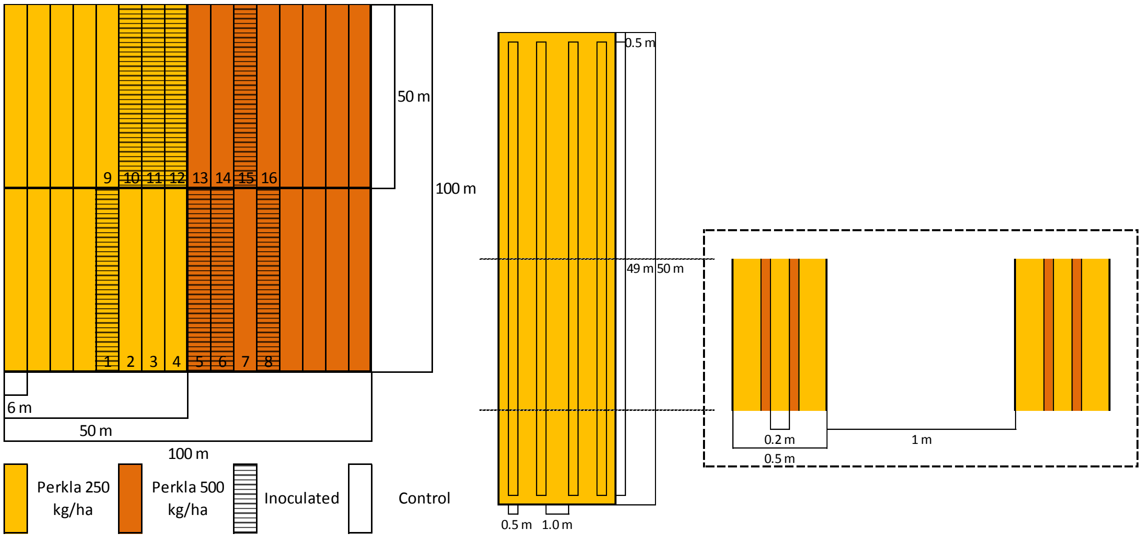


Figure 12 Layout of the trial with beans grown in hydroponics. On the left the whole field split into two halves with corresponding Perkla treatment (250 kg/ha and 500 kg/ha). In the middle the design of a single plot, consisting of four troughs. Plots were either inoculated with Legumefix at the rate of 400 g per 100 kg seed or left as a control. Each trough included two rows of runnerbeans, as indicated on the left.

3.2 Outgrowers trials

In agreement with the outgrowers 18 farms were selected, based on advice of the Liki River Outgrowers management. In the form of a simple interview with the farmer, basic information about the household and farm management was acquired. Soil samples (0 – 20 cm) were taken with a soil auger in a 'W' pattern across the experimental area on all farms. Areas of discontinuity such as termite mounds were avoided. The subsamples were mixed thoroughly and combined into a composite sample of approximately 1 kg per field and sent to the laboratory for analysis of pH, phosphorus, potassium, calcium, manganese, magnesium, sulphur, copper, boron, zinc, potassium, iron, aluminium, cat ion exchange capacity, EC (salts), Organic Matter, nitrogen, and percentage sand, silt and clay (Table 6) by the methods described in Section 3.4.

3.2.1 Field experiments

Trials were planted on the 23rd of May in Maritati/Kisima and on the 24th of May in Kirima/Rongai. A simple design consisting of three randomised treatments was made, as appears in Figure 13:

1. Two control plots without any N fertilizer and no inoculation (0);
2. A plot without N fertilizer, examining the effect of inoculation with Legumefix (+I);
3. A plot with N fertilizer (based on outgrowers' fertilizer use) and no inoculation (+N).

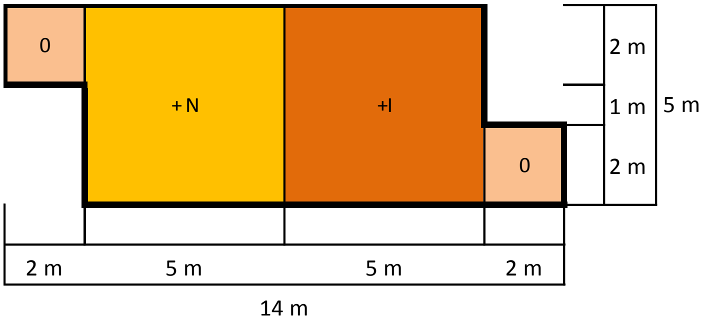


Figure 13 Plot layout of a satellite trial with two controls (0), a plot with Rhizobial inoculation (+I) and an N fertilizer (+N) treatment. Note that the positions of the treatments were randomized on each field. Measurements are an indication as they were adjusted depending on farmers' spacing. In some cases a larger single control plot was chosen. Gross trial size equalled approximately 68 m^2.

The plot examining inoculation and the one with additional fertilizer occupied approximately 25m^2, depending on farmers' spacing. In order to minimize farm impact the size of the control plot was kept to a minimal size in which measurements could still be made (approx. 4m^2). Two control plots were included, on either side of the other treatments, to reduce the risk of loss of the control by any cause. All plots were fertilized with phosphorus in the form of Triple Super Phosphate (TSP; 45% P2O5, rate 48 kg P/ha), based on current practices: farmers use approximately 15kg of DAP per 5 kg of seed.

Table 6 Soil characteristics of the selected sites.

Farm	Site/ Farmer	pH	OM	N	P	Ca	Mg	K	Na	C.E.C	EC	Mn	S	Cu	B	Zn	Fe	Al	Sand	Silt	Clay
			%	%	mg/kg	cmol/kg					uS/ cm	mg/kg							%		
	Maritati																				
1	Japheth Bundi	5.84	4.41	0.16	92.5	10.3	3.0	1.8	0.1	20.5	162	252	12.5	2.35	0.78	9.18	126	993	49.2	15.8	34.8
2	David Munene	6.17	4.49	0.22	103	11.5	3.1	2.7	0.2	21.4	177	256	13.3	3.30	1.04	21.8	122	970	52.5	14.9	32.5
3	Daniel Muriki	6.03	3.61	0.17	61.0	9.6	3.0	2.0	0.2	18.5	100	214	9.10	1.48	0.57	6.12	146	903	52.7	15.6	31.6
4	Eric Mutwiri	6.34	3.15	0.11	58.7	11.5	3.7	1.9	0.2	20.4	88.0	226	6.87	1.68	0.58	7.29	144	885	49.6	13.8	36.5
5	Anthony Waituika	5.53	3.91	0.17	81.8	9.4	2.4	1.9	0.5	22.1	157	276	16.5	2.53	0.68	3.09	130	1010	52.0	16.7	31.2
	Kisima																				
6	David Kimathi	7.04	5.83	0.26	145	18.2	4.7	3.9	0.3	28.3	130	192	11.1	3.05	1.21	12.7	153	790	48.9	14.1	36.8
7	Solomon Kimonye	5.82	4.87	0.21	101	15.2	2.9	0.7	0.3	26.1	64.0	212	7.03	2.78	0.64	9.26	150	981	50.0	15.4	34.5
8	Amara Kiende	6.91	5.49	0.20	59.6	16.5	5.4	2.1	0.3	25.9	91.0	229	8.94	1.84	1.01	6.15	93.4	841	49.2	13.8	36.8
9	Joseph Karemu	5.40	5.33	0.17	126	10.8	2.8	1.1	0.3	24.8	149	224	11.8	5.02	0.66	12.0	165	1070	56.0	13.6	30.3
10	Julius Kiburi	4.87	4.22	0.17	9.18	5.0	1.6	1.1	0.2	17.8	94.0	296	18.9	2.01	0.48	2.46	107	1220	46.9	8.56	44.5
	Kirima																				
11	Isaac Kihara	5.81	3.16	0.13	56.5	14.2	3.8	1.4	0.5	27.2	70.0	177	9.53	1.09	0.57	3.44	160	783	48.5	7.28	44.1
12	Isaac Kamau	5.82	3.52	0.15	73.1	16.4	3.8	1.7	0.3	30.1	66.0	120	7.29	0.92	0.57	2.42	142	684	50.5	9.27	40.1
13	Njeri Wangechi	6.08	2.35	0.12	19.8	9.0	2.7	1.4	0.2	16.5	52.0	226	8.09	1.40	0.50	2.71	163	829	52.9	14.5	32.5
14	Joseph Muriithi	6.43	3.09	0.11	3.20	16.3	3.6	1.2	0.9	25.5	77.0	211	7.42	1.25	0.70	4.36	117	661	52.2	10.9	36.8
	Rongai																				
15	Kabuku Kamanga	7.22	3.50	0.17	68.2	21.7	4.5	2.8	0.9	31.3	99.0	297	8.52	1.48	0.93	12.6	73.0	700	56.5	7.28	36.1
16	Francis Mwarano	7.13	3.09	0.14	15.5	27.5	3.3	1.7	1.1	35.3	165	299	8.40	1.29	0.99	97.5	55.3	615	48.2	15.6	36.1
17	Gerald Gichuki	6.24	3.71	0.16	49.0	22.7	3.5	1.4	0.4	33.6	146	223	11.3	1.38	0.86	3.47	96.5	695	50.5	11.6	37.7
18	Patricia Njeri	7.42	2.76	0.11	21.0	32.8	3.9	1.3	0.7	40.5	110	254	8.11	1.13	0.97	3.31	54.7	663	52.9	9.27	37.7

Depending on farmer preference the legume type seeded was Garden pea cv 'Somerwood', Snow pea cv. 'Kennedy' or Sugar Snap cv. 'Cascadia'. For the +N treatment the plot was fertilized with nitrogen in the form of urea (46% N) at the rate of 54 kg N/ha. Inoculation rate for the +I treatment was 400 g for 100 kg of seed. The seeds were thoroughly mixed with Legumefix in the shade and sown immediately. Care was taken to avoid cross contamination of uninoculated seeds and plots with rhizobia, by planting the uninoculated seeds before the inoculated seeds. Other management remained as farmers practice.

Plants in each plot ware evaluated in terms of general vigour (by observation) and pod fresh weight was recorded at harvest for each treatment.

3.3 Laboratory analysis

Soils sampling and plant nitrogen concentration analysis was performed by Crop Nutrition Laboratory Services in Nairobi. Table 7 provides an overview of all the methods used.

Table 7 Analysis methods used by Crop Nutrition Laboratory Services

Parameter	Method	Description
Soil pH	Potentiometric	Soil : Water 1: 2
Soil EC	Potentiometric	Soil : water 1: 2
Extractable Soil Ca, Mg, K, Na, Mn, Fe, Cu, Mo, B, Zn, S	Atomic Emission spectrometry (ICP-AES)	Mehlich 3 – Diluted ammonium fluoride and ammonium nitrate
Soil Available Phosphorus (P Olsen)	Colorimetric	Sodium bicarbonate Extractant. Colorimetric analysis using the molybdenum blue method
Soil Carbon	Walkley and Black Method	Wet oxidation by acidified dichromate in the presence of sulphuric acid
Plant Total Nitrogen	Titrimetric	Kjeldahl digestion (Sulphuric acid + H_2O_2 wet digestion) then semi-micro distillation.

3.4 Data analysis

All the data were subjected to Analysis of Variance (ANOVA) using the ANOVA Procedure of Genstat version 15 and differences among the treatment means compared using Fisher's Protected LSD test at 5% probability level. The two main field experiments were analysed using the split-plot design procedure. General analysis of variance was used for the trial in hydroponics, with the Perkla treatment as the block structure and inoculation as the treatment. Similarly the general analysis of variance was used for the outgrower trials. Here each location was considered as a separate block.

Correlations between the majority of the obtained socio-economic, biophysical and agrological factors were detected with Spearman's correlation tables.

3.5 Economic valuation

A comparison was made between current management, the results of the Legumefix treatments and the cheapest alternative form of N, urea. Table 8 shows the assumptions used for making calculations. These are based on information received from the company.

For the company accumulated N costs per year were calculated for each management type by:

$$\text{Accumulated N costs} = 728 \times \text{price per ha} \qquad \text{(eq. 3)}$$

The partial budget (PB) was calculated for the company and the outgrowers'via:

$$\text{PB} = \text{yield} \times \text{price} - \text{inputs} \times \text{costs of inputs} \qquad \text{(eq 4.)}$$

Table 8 Assumptions for economic valuation

Assumption	Amount	Unit
Company characteristics		
Area of beans grown	728	ha/year
Seeding rate	60	kg/ha
N use	120	kg/ha
Average yield*	10.2	t/ha
Sales	0.50	USD/kg
Outgrowers characteristics		
Fertilizer use	300	kg DAP/ha
Seeding rate	50	kg/ha
Sales	0.83	USD/kg
Prices		
N costs farm	600	USD/ha
Legumefix	10	USD/package
Urea	400	USD/t
DAP	0.6	USD/kg
Other		
Legumefix rate	4	g/kg of seed

* average company yield over the last 12 months

4. Results

4.1 Longonot experiments

Emergence, establishment, growth

All field trials emerged and established well although some plots on the field borders of the common bean trial were affected by antelopes feeding on the young crop. As a result establishment was reduced to approximately 84% over the entire trial. An interaction effect of inoculation and nitrogen supply on establishment was indicated by the analysis of variance (*P*=0.019), but no trend could be observed (Table 9). The plots that were inoculated with Biofix and received 0 kg of N per hectare established poorer (76%) than the rest of the trial. This was related to two plots on the border that were heavily attacked.

Table 9 The combined effect of inoculation and N supply on the establishment of the bean trial (% of plants established)

Inoculation treatment	N (kg/ha) 0	30	60
Legumefix	81	88	86
Biofix	76	83	88
Control	89	82	88
Mean	82	84	87

P=0.019, LSD=11.1
P=0.053, LSD=4.5 for all means

The beans and peas grown displayed a vigorous growth but at the time of harvest for common bean trial, and of early flowering for the garden peas, heavy hail hit the experimental site at Longonot (Figure 14). At this stage the common bean trial had just been picked for the first time. Standard practice is to harvest continuously for several weeks, however the damage caused by the hailstorm was severe to such an extent that it terminated the trial. As a result yield data are incomplete. Similarly the pea trial was affected. Although damage was severe it was decided to continue growing. Nevertheless results turned out highly variable and insignificant for this trial (Appendix X & XI). Thus, besides the appendices, henceforth no further data about the pea trial will be presented. Finally, appendix IX presents the result of the analysis of plant N, in which also no significant results were found.

4.1.1 *Phaseolus vulgaris* L. cv. 'Serengeti'

Fertilizer effects

In accordance with common theory (Bekunda et al., 2010) mineral N supply had a negative effect on nodulation (*P*≤0.001) and a positive effect on biomass (*P*=0.013) (Table 10). Surprisingly it did not have an effect on yield (*P*=0.122)

Table 10 The effect of N supply on mean nodule score, yield and biomass.

Measurement	N (kg/ha) 0	30	60
Nodule score[a]	3.04	2.58	2.3
Yield [b]	7542	8015	8330
Plant biomass (kg/ha)[c]	16063	17336	18486

[a] *P*≤0.001, LSD=0.228
[b] not significant
[c] *P*=0.013, LSD=1591.0

Figure 14 heavy hail caused severe damage to the trials at Longonot

No effect of P fertilizers on nodulation or yield was found, nor were any interactions between fertilizers and inoculation proven to have a combined effect. This data is presented in the appendices IV-VII.

Effects of inoculation on nodulation

Means of plots inoculated with Legumefix were higher in nodulation score (2.9) than uninoculated plots (2.6) or plots inoculated with Biofix (2.4) (Figure 15). There was no difference between Biofix and the uninoculated plots (*P*=0.010).

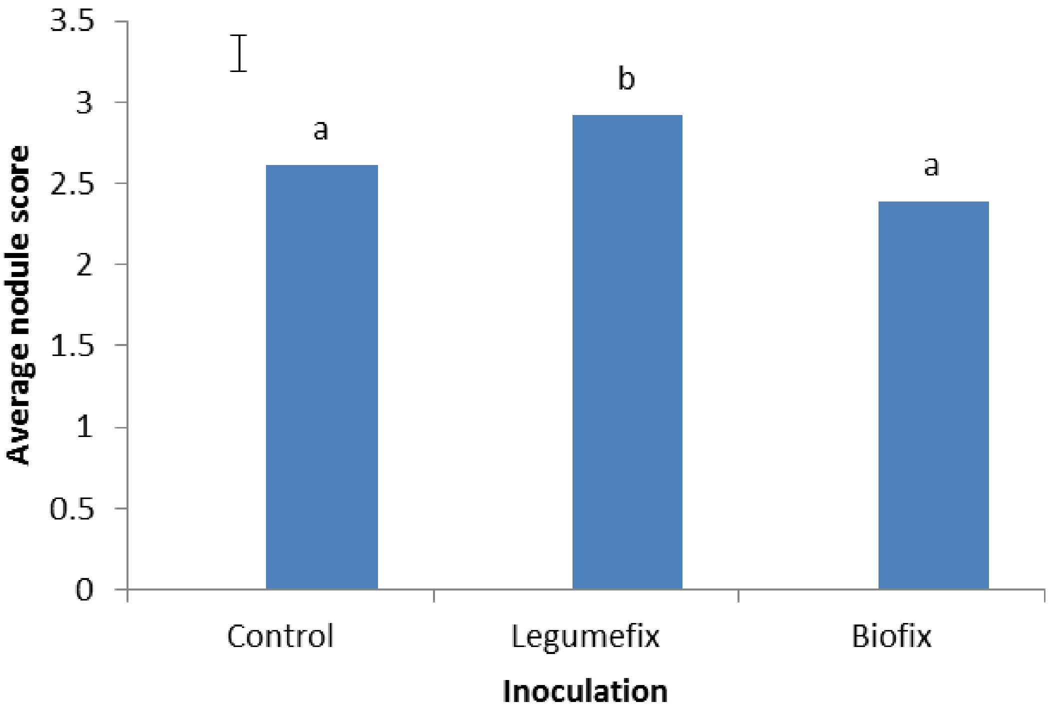


Figure 15 Means of average nodule score for three different inoculation treatments. Average nodule score reported as calculated average of six samples per plot. Different letters indicate significant difference with LSD: 0.277 at *P*≤0.05.

Effects of inoculation on yield

Overall yields were greatest where Legumefix was used (8.5 t/ha), intermediate for Biofix (8.0 t/ha) and poorest in the control treatment (7.4 t/ha) (Figure 16). There was no difference between the control and Biofix, but Legumefix increased the yields when compared with the control treatment, however only at *P*=0.059.

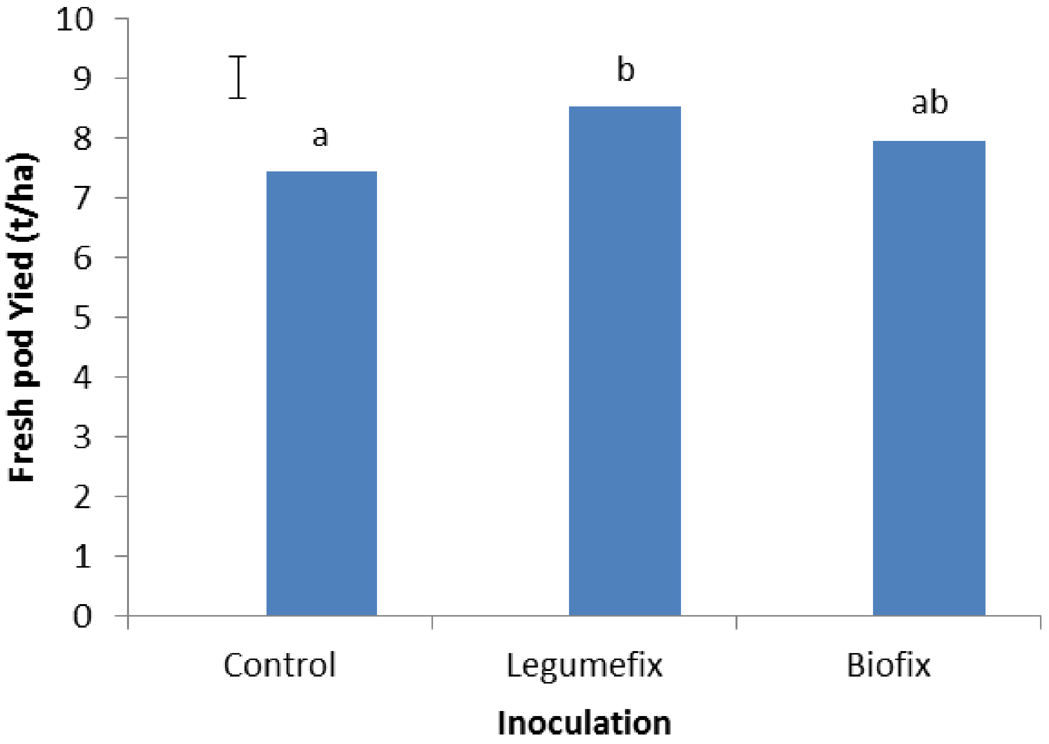


Figure 16 Mean yields for the three different inoculation treatments. Different letters indicate significant difference with LSD: 0.87 at *P*=0.059.

Plant density at time of harvest turned out to be higher for the control treatment (*P*=0.011) (Figure 17). On average the control treatments had a plant density of 357,000 plants per hectare. The Legumefix and the Biofix treatments were 311,000 and 307,000 plants per hectare respectively. Hence, the number of plants per hectare in the control treatment was roughly 15% higher than in the inoculated plots. Using Spearman's rank correlation coefficient it turns out that plant density was positively correlated to yield, but this correlation was very small (0.2, $P \leq 0.01$).

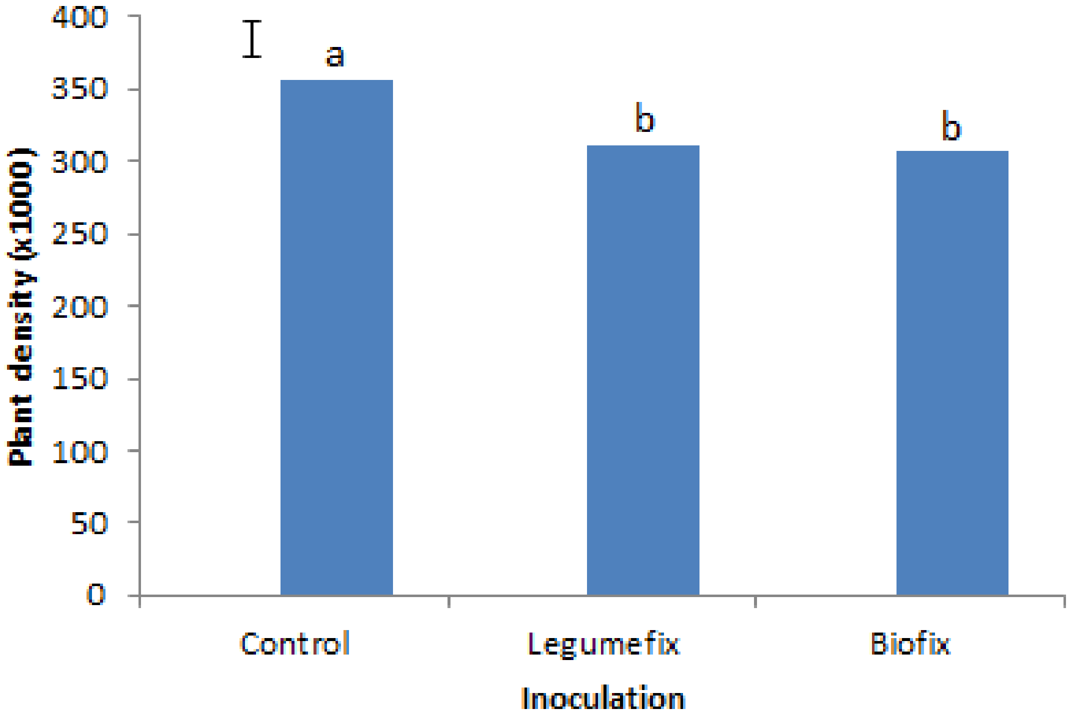


Figure 17 Mean plant density of the *Phaseolus vulgaris* L. trial. Different letters indicate a significant difference at LSD= 29436.2 and *P*=0.011.

Figure 18 shows the yield per plant was higher for both the Biofix and the Legumefix treatment, compared to the control (0.021 kg/plant) (*P*=0.022). Legumefix yielded over 33% more (0.028 kg/plant), whereas the yield of Biofix was 24% higher on a per plant basis (0.021 kg/plant).

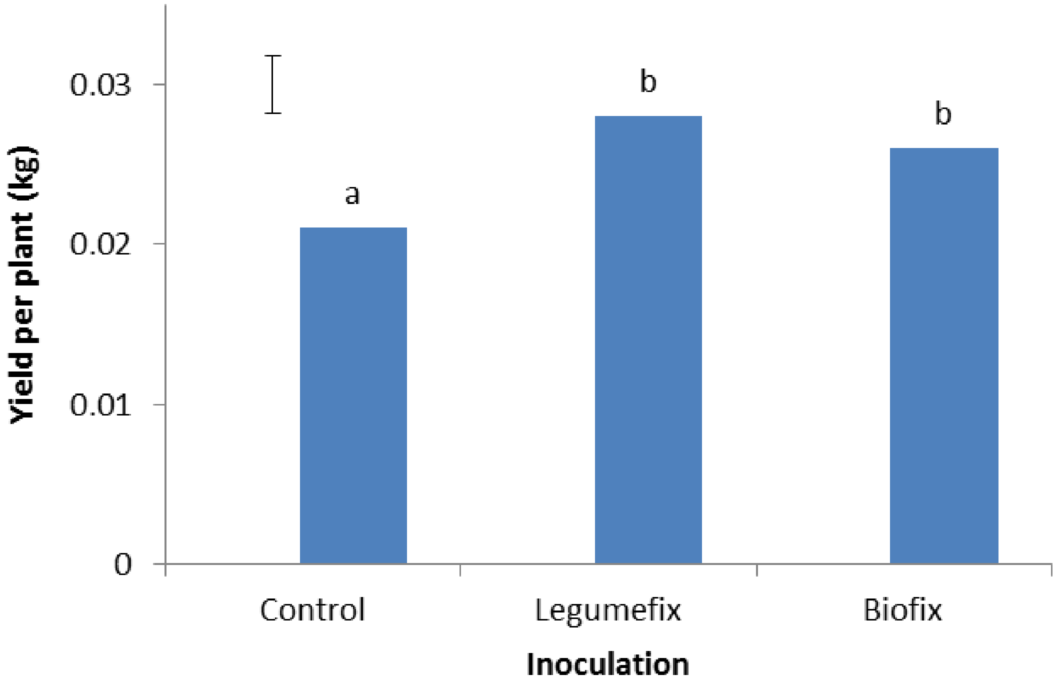


Figure 18 Mean yields per plant for the three different inoculation treatments. Different letters indicate significant difference with LSD: 0.0045 at *P*=0.022.

4.1.2 Hydroponic runner beans *Phaseolus vulgaris* L. cv. 'White Emergo'

Means of nodulation score (2.58 for the inoculation treatment vs. 2.10 for the control) were not significantly different (*P*=0.102), however the distributions demonstrated a very different picture between the two groups (Figure 19). Medians were 2.08 for the control and 2.67 for the plants inoculated with Legumefix. Both showed a maximum of 3.17 but in the case of the control this score was an outlier. By contrast, this score was part of the 1.5 interquartile range for the Legumefix treatment, which showed a negative outlier (score 1.33). When not taking into account these outliers the analysis shows *P*≤0.001. No defferences were found between the Perkla treatments (*P*=0.214).

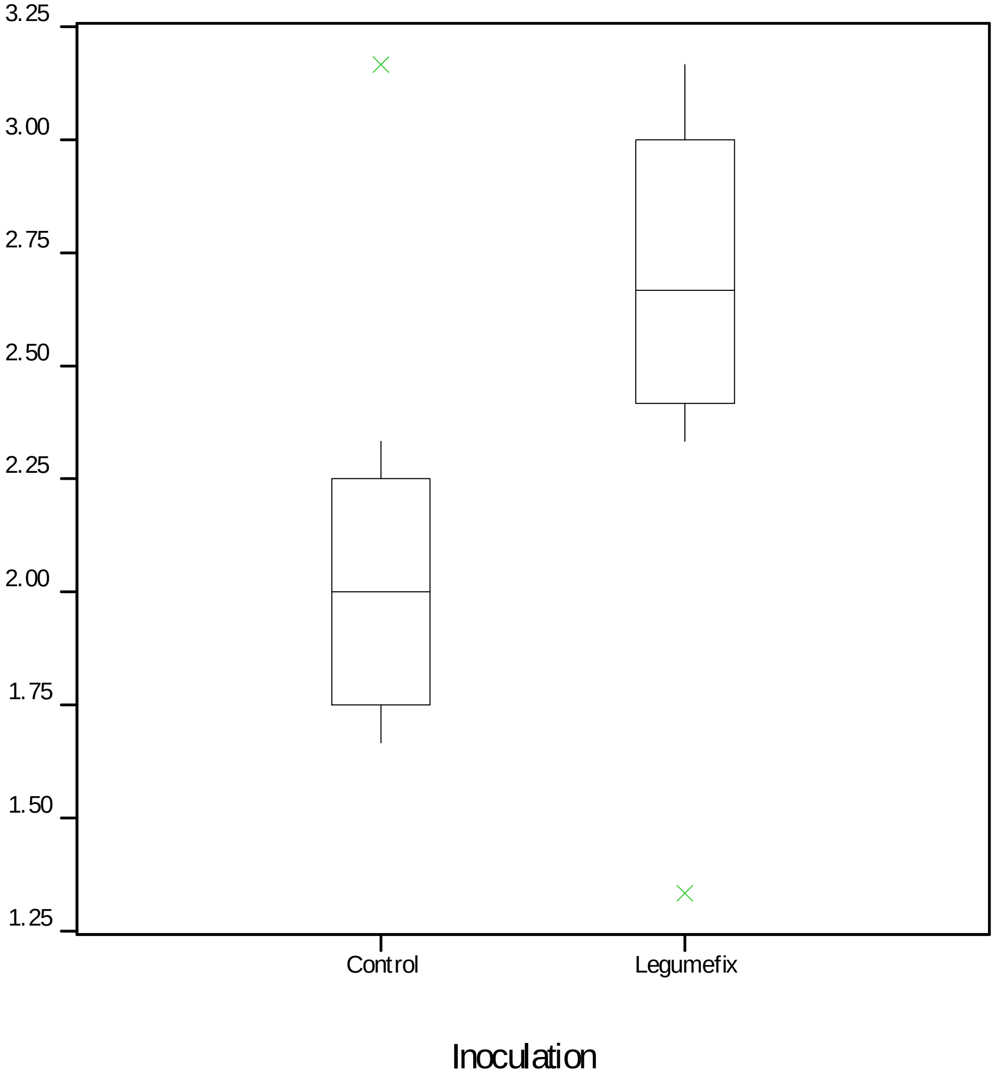


Figure 19 Boxplot of average nodulation scores for Legumefix inoculated plants and the control (n=8) (*P*=0.102). Average scores are the result of summing the individual scores of 6 samples per plot and calculating the average.

4.1.3 Economic valuation

Table 11 shows the accumulated costs per year over the three management types and the partial budgets. Without a complete yield for the Legumefix treatments no calculations could be made for this management type.

Under current management the costs of N fertilizers add up to 437,000 USD per year. If all of this would be replaced by Legumefix the cost would amount 7,280 USD per year; a 98% difference. The price of N in the form of urea was 76,000 USD. Although only 17 % of the current costs of N this is still over ten times as much as the costs of Legumefix.

The partial budget for current management was equal to 3.28 million USD per year and 3.64 million for N in the form of urea.

Table 11 Comparison of N costs and partial budget of current management vs. the use of Legumefix and urea as N source

Management type	Yield (t/ha)	Price (USD/kg)	Sales (USD/yr)	N supply (kg/ha)	Costs of N (USD/ha)	Accumulated N costs (USD/yr)	Partial budget (USD/yr)
Current	10.2	0.5	3712800	120	600	436,800	3,276,000
Legumefix	-	0.5	-	Inoculation	10	7,280	-
Urea	10.2	0.5	3712800	120	104	75,965	3,636,835

4.2 Outgrower trials

4.2.1 Interview results

With a single exception all farms were managed by the owner, whose income was fully derived from working at the farm (Table 12). A negative correlation (-0.675) was found between household size and farm size ($P \leq 0.05$). No further relationships were found between indicators. Both amount of hired labour and livestock ownership showed a lot of variability. All farm owners kept cows (data missing for one farmer), seven also owned sheep and/or goat (two).

Table 12 Socio-economic characteristics of the outgrowers' as answered in the interviews.

Farm	Location	Farm size (ha)	Household size (number)	Education (level)	Income (type)	Hired labour (type)	Hired labourers (number)	Livestock* (animal)	Livestock ownership (number)
	Meru								
1	Maritati	2.4	5	Primary	Farm only	Full time	1	Cow	6
2		1.2	4	Primary	Farm only	Full time	7	Cow	5
3		2.0	3	Primary	Farm only	Full time	2	Cow, sheep	2+10
4		0.9	4	Secondary	Farm only	Casual	-	Cow	4
5		3.2	-	-	Manager	Full time	7	None	0
6	Kisima	0.4	6	Primary	Farm only	Casual	-	Cow, sheep	2+3
7		0.4	6	Primary	Farm only	Full time	2	Cow, sheep	3+10
8		0.4	8	Secondary	Farm only	Casual	1	Cow	1
9		2.4	4	College	Farm only	Full time + casual	1+3	Cow, sheep, Goat	3+5+4
10		0.4	4	Secondary	Farm only	-	-	Cow, sheep	2+7
	Njeri								
11	Kirima	1.2	2	Primary	Farm only	None	-	Cow	1
12		0.6	5	Secondary	Farm only	Casual	2	Cow	2
13		1.6	6	Secondary	Farm only	Casual	6	Cow, Goat	5+1
14		0.6	6	Secondary	Farm only	Casual	2	Cow	2
15	Rongai	1.2	5	Primary	Farm only	Full time	8	Cow, sheep	4+3
16		1.1	-	Higher	Farm only	Casual	-	-	-
17		0.7	4	-	Farm only	Casual	3	Cow, sheep	3+2
18		1.4	5	Military	Farm only	Casual	-	Cow	2

*cows improved

Apart from peas, potato was the dominant crops in all areas, grown by all farmers in Maritati, Kisima and Kirima and by half of the farmers in Rongai (Table 13). It was followed by maize (12), bean (6), cabbage (5), carrot (3) and onion (1). Beans were only grown in Njeri district. Surprisingly also growing beans did not increase the percentage of land for growing legumes; farmers in Njeri allocated a smaller proportion of land to legumes than their counterparts in Meru, both in percentage (27% vs. 41%) and absolute amounts (0.2 ha and 0.4 ha respectively).

Table 13 Outgrower management characteristics as answered in the interviews

Farm	Location	Current crops[ab]	Area sown to legumes (%)	Area sown to legumes (ha)	Proportion of crop consumed[c] (%)	Livestock Form	Manure use[d]	Crop residue use	Other feed	Weeding
	Meru		*41*	*0.4*						
1	Maritati	M, P	50	1.2	100	0-grazing	Crop	Livestock	-	Manually
2		C, P	33	0.4	10	0-grazing	Crop	Livestock	-	Manually
3		C, Ca, P	25	0.5	-	0-grazing	Crop	Livestock	-	Manually
4		M, P	50	0.5	0	0-grazing	Sold	Livestock	-	Manually, herbicide, tillage
5		P	-	-	0	-	-	-	-	-
6	Kisima	C, P	50	0.2	-	0-grazing	Crop	Livestock	Napier, hey	Manually
7		M, P	70	0.3	-	0-grazing	Crop	Livestock	Napier, hey	Manually
8		Ca, P	50	0.2	-	0-grazing	Crop	Livestock	Napier, dairy feed	Manually
9		Ca, M, O, P	17	0.4	10	0-grazing	-	Livestock	-	-
10		M, P	25	0.1	-	0-grazing	Crop	Incorporate	-	Manually
	Njeri		*27*	*0.2*						
11	Kirima	M, P	17	0.2	50	Grazing	-	Incorporate	-	Manually
12		B, M, P	-	-	-	Grazing	Crop	-	-	Manually
13		B, C, M, P	25	0.4	10	Grazing	Crop	Incorporate	-	Manually
14		B, P	33	0.2	-	Grazing	Crop	Livestock	-	Manually
15	Rongai	B, C, M, P	25	0.3	-	Grazing	Crop	Incorporate	-	Manually
16		M	50	0.5	-	-	-	Incorporate	-	Manually, herbicide
17		B, M	25	0.2	-	Grazing	-	Livestock	-	Manually
18		B, M, P	15	0.2	33	Grazing	Crop	Livestock	Napier	Manually

[a] Other than Peas. B=bean, C=cabbage, Ca=carrot, M=maize, O=onion, P=potato.
[b] Peas received mineral fertilizers based on Liki recommendations.
[c] Other than peas; all peas were sold to Liki outgrowers.
[d] As part of Liki Outgrowers no manure is used on peas.

On all farms weeding was done manually, in two cases accompanied by the use of herbicides. One of these two farmers also practiced tillage as a form of weed control.

All livestock in Meru district was kept in the form of 0-grazing, whereas those in Njeri district grazed freely. A single farmer in Meru incorporated his crop residues but overall it was used as feed. In three cases additional feed in the form of napier grass (3), hey (2) or specialized dairy feed (1) was also supplied. Additional napier was also supplied by one farmer in Njeri. Crop residue use in this district varied between the two different options. Finally, although one farmer had decided to market it to neighbouring farmers, in all other cases manure was allocated to crops in both of the districts.

When asked to rate the importance of growing legumes for their farm on a scale from one to six, with six indicating 'most important', all farmers indicated a score of four or above (Table 14). Five of them valued legumes as very important (5) and half even indicated the highest score. One farmer was not available to answer the question. Generally the motivation for growing legumes was cash income but also labour requirements, agronomy and source of food was mentioned. None of the outgrowers ever had any previous experience with the use of inoculants or had heard about the technology before.

Table 14 Outgrower opinions on legume importance, growth and limitations as answered in the interviews

Farm	Area	Legume importance (1-6 scale, 6=highest)	Motivation for growing legumes	Growing limitations	Input limitations	Previous knowledge about rhizobium
	Meru	*5.2*				
1	Maritati	6	Cash	Water	Financial	None
2		5	Labour	Water	Financial	None
3		5	-	Water	None	None
4		6	Cash	Weather	None	None
5		-	-	Financial	Financial	None
6	Kisima	5	Cash	Water, Market	Financial, Market	None
7		6	Cash	Water, Market	Financial	None
8		6	Cash	Water	Financial	None
9		4	Cash	Financial	Financial	None
10		4	Cash	Disease, Weather	None	None
	Njeri	*5.5*				
11	Kirima	6	Cash	Water, Financial	Financial	None
12		6	Cash	Market, Financial	Financial	None
13		4	Cash	Water	Financial	None
14		6	Cash	Water	Market	None
15	Rongai	6	Cash	Financial	Financial	None
16		5	Cash, food	Disease	None	None
17		5	Agronomy	Market	Financial	None
18		6	Cash	Water	Financial	None

Limiting factors in growing legumes were described as either water/weather, mentioned by 12 farmers and/or market/financially related (8 times). Disease was only indicated twice. In terms of inputs, 13 farmers declared financial issues were limiting, whereas four stated they did not have any problems at all. In two cases market was mentioned as a constraint of using more inputs.

4.2.2 Trial results

Due to disease pressure (e.g. thrips) seven outgrowers aborted the trials. These included the three garden pea trials, two snow pea trials and one sugar snap pea trial. Likewise, two farmers that grew snow pea were not able to finish the full harvest cycle before disease pressure became too severe. As a result only eight data points are available for total yield evaluation. Furthermore, the control plots showed highly retarded growth and farmers stopped taking care of them.

Figure 20 shows the accumulated yields of each urea treatment and its corresponding treatment with Legumefix. On average the snow pea plots treated with Legumefix yielded 30% more than the ones treated with urea (means 6.4 t/ha vs. 4.9 t/ha, P=0.003). However, this included two negative outliers that were the result of an uncompleted harvest cycle due to disease pressure. When these outliers were excluded means increased to 7.9 t/ha for Legumefix and 5.9 t/ha for urea respectively. In this case Legumefix gave 33% higher yields ($P \leq 0.001$) but the minimum yield for the inoculated plots (4.4 t/ha) was lower than that of the urea treated plots (4.8 t/ha). Furthermore, urea showed a negative skew with the median at 6.2 t/ha, whereas the Legumefix treatment was more normally distributed with the median located at 8.1 t/ha. Lastly, the sugar snap variety under *Rhizobium* underperformed compared to the N treatment but this is only a single observation.

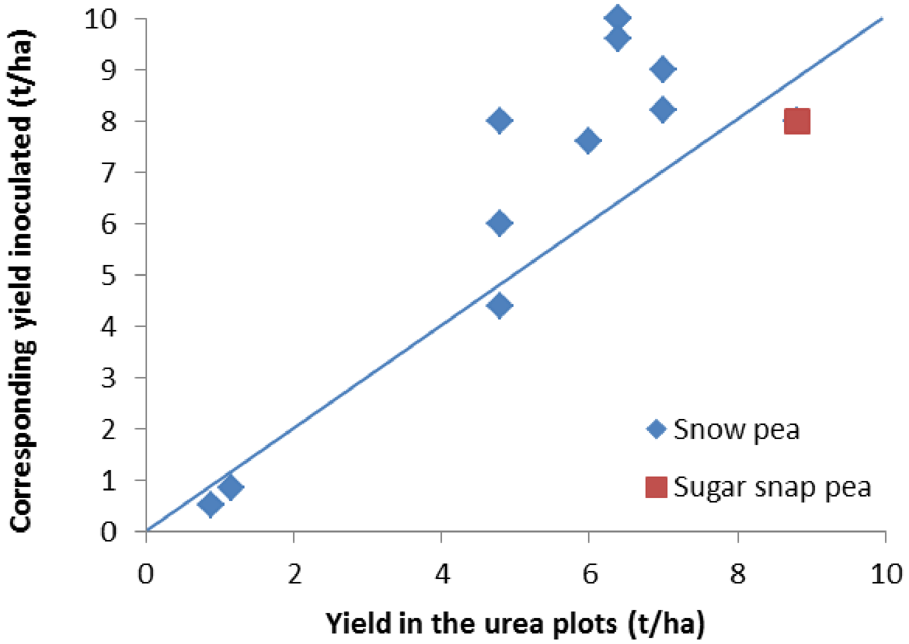


Figure 20 Accumulated yield of each urea treatment and its corresponding treatment with Legumefix (n=11). The low outliers were a result of an uncompleted harvest cycle due to disease pressure. The line indicates the 1:1 ratio.

4.2.3 economic valuation

Outgrowers use 50kg of seeds per ha, so costs of inoculation would be only 8.30 USD, a 95% reduction in costs of inputs (Table 15). The costs of N in the form of urea were 47 USD/ha, over five times higher than using Legumefix. Assuming the yields achieved in the snow pea trials, excluding outliers, a partial budget of 4,700 USD ha^{-1} was calculated for current management. Using inoculation with Legumefix instead would result in 6,400 USD ha^{-1} to be earned, an increase of 35%.

Table 14 Comparison of N costs and partial budget of current outgrower management vs. the use of Legumefix and urea as for of N

Management type	Yield (t/ha)	Price (USD/kg)	Sales (USD/ha)	N supply (kg/ha)	Costs of N (USD/ha)	Partial budget (USD/ha)
Current	5.9	0.83	4,897	54	180	4,717
Legumefix	7.7	0.83	6,391	Inoculation	8.3	6,383
Urea	5.9	0.83	4,897	54	47	4,850

5. Discussion

5.1 Longonot

5.1.1 Effect of fertilizers and inoculation on nodulation of *P. vulgaris*

Fertilizers

Number of nodules was negatively affected by mineral N supply, as would be expected according to common knowledge: with adequate levels of soil- or fertilizer-N (application levels above 25kg N ha-1 or more) BNF is suppressed (Bekunda et al., 2010):

The addition of P fertilizers did not affect nodulation, indicating P was not limiting at this site. In accordance with the soil characteristics of this site (Table 5) this is what would be expected, as available soil P was very high (109 mg kg^{-1}).

Inoculation

Inoculation with Legumefix increased nodulation, both in the field trial as well as in the runner beans. In the case of the runner beans this is not a significant result, but the distribution seems to indicate a possible difference. When the outliers are left out this picture is further reinforced and the analysis shows a significant difference. A surprising result considering 1) the runner beans received a large amount of mineral N via their feeding solution; and 2) intuitively, especially in terms of organic matter, the pumice does not seem a suitable medium for *Rhizobium* to survive. In the case of the latter, as the pumice was used for the third consecutive season some organic remains of previous seasons may have been be prominent. Nevertheless, as a first indication this provides a purpose into further looking into increasing the use of inoculation as a management option.

In the bean field trial the uninoculated plots nodulated well, suggesting the population of indigenous rhizobia which could nodulate *P. vulgaris* was sufficient. This is further supported by Anyango *et al*. (1995), who estimated the size of the population of rhizobia capable of nodulating *P. vulgaris* in a Naivasha soil to be 1.47 x 10^4 cells per g of soil. The soil used in this experiment was taken from a similar area in the soil classification by Jaetzold *et al.* (2010). According to Giller *et al.* (1998) responses to inoculation are generally not found if the population of indigenous, effective rhizobia for the legume of interest is larger than 50-100 cells per g of soil, clearly the case for the soil described by Anyango *et al.*. Moreover, absence of compatible rhizobia is somewhat unlikely in the case of *P. vulgaris*, due to its promiscuity of nodulation (Giller, 2001). Legumefix outperformed the control and the Biofix treatments nonetheless, whereas Biofix did not cause any change in nodulation compared with the control. As both inoculants use the same strain of *Rhizobium* this cannot be related to genotype. In this context, Legumefix must have been highly competitive in a different characteristic, possibly related to larger numbers of rhizobia per gram of inoculant.

5.1.2 Effect of fertilizers and inoculation on yield of *P. vulgaris*

Plant density

Unexpectedly plant density turned out to be significantly larger for the control treatment (Figure 17). In fact, it was even higher than the proposed density. It is unclear what could have caused this. As the planting density turned out to be positively correlated to yield perhaps the control yield may have been slightly larger than expected. Hence, the difference in yield between the control and the inoculation treatments could have been larger. The correlation was only marginal however, and there was no difference between plots in total amount of biomass (Appendix VII) suggesting there may have been compensatory growth in the other treatments: on a per plant basis plants grew slightly larger in the non-control plots. This could be explained by reduced competition due to the absence of a neighbouring plant. The yield per plant (Figure 18) supports this argument. In fact, on average plants inoculated with Legumefix yielded up to even a third more. This is a lot more than just a compensation for the 15% difference in plant density though.

Fertilizers

P fertilizers had no effect on yield as sufficient P was available from the soil (Table 5). Surprisingly mineral N did not have an effect on yield, but a positive trend was visible.

Inoculation

Legumefix increased the mean yield by almost 15% compared to the control (Figure 16) and also outperformed the Biofix treatment by 7%. In other words, Biofix also increased yields, but underachieved when compared to the Legumefix treatment. As this is only a partial yield due to the weather circumstances it is difficult to interpret these numbers, but in combination with the result of the nodule scoring, it suggest Legumefix to be the superior product, and capable of increasing yields.

Interestingly the company's average total yield over the same growing season as the trial ± 14 days was 7.9 t/ha (from 12 growing cycles grown on blocks of comparable soil, data not presented). In this season the average number of pickings was equal to 6.3 times with roughly the same number of days to first picking. The amounts harvested the first full pick (usually in two consecutive picks, related to labour requirements) were equal to 3.9 t/ha on average. The figures used for these calculations were variable, but it is a remarkable observation that the trial's mean yield under Legumefix (8.5 t/ha) was almost 8% higher than the average total harvest; more than double the average first full picking and also 30% larger than the largest observation for a first picking (6.4 t/ha). Furthermore the smallest yields in the trial (5.3 t/ha for Legumefix and 5.2 t/ha for Biofix) were larger than 75 % of the company's first picks, and a third larger than their average.

Extrapolating the data to an entire season would be mere speculation but, assuming the previous averages of 7.9 t/ha in total yield and 3.9 tons in the first full pick, would mean 50.3% of the trial's yield was still to be harvested after the first full pick. Using this number to calculate the theoretical full yield adds up to the average yield under Legumefix possibly having reached as high as 17.1 t/ha. For comparison, the highest company yield in the same season was 14.7 tons/ha. It is doubtful whether this calculation holds any value considering the average control treatment also performed well. Nonetheless, irrespective of the underlying causes it is clear there may be room for improvement of current yields and increasing reliance on BNF could play an important role.

Finally, even though no interactions between nitrogen treatments and inoculation were found (Appendix V), out of the 14 plots that gave a yield of 10 t/ha or more, only one was not supplied with any N. Exactly half were supplied with 60 kg of N ha^{-1}. Therefore there may be opportunities for making use of a combination of mineral N and inoculation. As mentioned in Section 1 mineral N supply is known to have a negative effect on BNF, so providing the crop with organic N is a delicate matter, but possibly starter N options could be explored.

5.1.3 Economic valuation

The calculations in table 11 show a reduction of 98 % in N input costs over current management when using Legumefix. Furthermore, the use of Legumefix was also shown to be 10 times cheaper than the cheapest form of N (urea). This does not necessarily mean costs of input can be one on one replaced by inoculation however. Under current management large quantities of N are supplied in combination with phosphate, potash, calcium or sulphur, which would have to be supplied in a different form. The soil sample taken from this field showed no critical values on these inputs though (Table 5) and the trial yielded very well without them. Hence, other inputs may also be reduced. For instance, the soil sample showed a high amount of available P. A dose to maintain these levels would in this case be sufficient. On other fields this may not be the case however. Nevertheless even reducing the N inputs by half would result in a considerable saving in costs of inputs. And considering the starter N option briefly discussed in Section 5.1.2, inoculation may be beneficial with some N inputs still in place. Hence, not all combined inputs may have to be replaced.

The partial budget analysis showed an income of 3.7 million USD per year was generated under current management. Hence, costs of N inputs amount to 12% of the crop value, implicating a great potential of reducing these costs and further researching an increased reliance on BNF. Unfortunately the partial budget for Legumefix could not be calculated due to the incomplete harvesting, but when assuming the potential yield (17.1 t/ha) that was extrapolated in Section 5.1.2 a partial budget for Legumefix can still be made (Table 16). This would implicate a partial budget of 6.2 million USD per year, 90 % higher than the partial budget under current management. As mentioned in Section 5.1.2 this is a very gross extrapolation, so no solid conclusions should be made from this figure, but it is an indication that increasing reliance on BNF may have great economic benefits.

Table 15 Comparison of N costs and partial budget of current management vs. the use of Legumefix and urea as N source

Management type	Yield (t/ha)	Price (USD/kg)	Sales (USD/yr)	N supply (kg/ha)	Costs of N (USD/ha)	Accumulated N costs (USD/yr)	Partial budget (USD/yr)
Current	10.2	0.5	3712800	120	600	436,800	3,276,000
Legumefix	17.1	0.5	6224400	Inoculation	10	7,280	6,217,120
Urea	10.2	0.5	3712800	120	104	75,965	3,636,835

5.2 Liki River Outgrowers

5.2.1 Soil analysis

Generally the soils analysed in this trial were relatively fertile (Table 6).With a few exceptions the soil samples showed the locations had plenty of organic matter, available P, major cations and a good Ca/Mg ratio.

5.2.2 Farmer characterization

Tittonell et al. (Tittonell et al., 2005) identified five representative farm types, which together represent much of the variability found in the highlands of western Kenya. These were identified using socio-economic information and considering production activities, household objectives and the main constraints faced by farmers. Based on this typology, with the exception of farm number 5, all outgrowers that collaborated in this research can be classified as type 3: Medium resource endowment, production orientated at self-consumption and marketing of surpluses, with their main constraint being capital (Table 12). All indicated the growing of legumes as very important as it was a main source of cash income. The fact that all are in the same category may not be fully representative for the Mount Kenya area. More variability would be expected. But all of them are affiliated with Liki River Outgrowers. The management scheme may attract and target a specific type of farmers. Consequently the farmers that cooperated in this research are in fact a sample of the Liki Outgrowers, rather than a true representation of the mount Kenya area.

Surprisingly the only significant correlation that was found between the indicators from the interviews was the negative correlation between household size and farm size. No arguments were found to explain this correlation.

5.2.3 Inoculation versus current management of *P. sativum*

Overall the inoculated treatments did better than current management (Figure 20). When not taking into account the two outliers and the sugar snap variety, only one of 8 observations revealed the current management to do better (4.8 t/ha vs. 4.4 t/ha) The corresponding soil analysis (farm nr 4) did not show any limiting factors for BNF. Furthermore, two observations show higher corresponding yields (6 t/ha and 8 t/ha) at similar sized yield under urea.

The result is a strong indication inoculation can contribute to increasing outgrower yields. As the sugar snap observation is only a single one it is not possible to derive any conclusions for this variety. Therefore it is advised to do some more extensive testing to find out if the technology works.

5.2.4 Economic valuation

The partial budgets presented in Table 15 show a clear benefit of the use of Legumefix. This was largely related to increased yields, but also to a large reduction of input costs. Consequently, profits and farm income can be increased by adoption of the technology.

6. Conclusions and Recommendations

6.1 Longonot trials

6.1.1 *P. vulgaris*

1. Both in terms of nodulation and yields Legumefix outperformed Biofix, indicating it is the superior product. When further looking into the use of inoculants the use of Legumefix should be the choice of preference if possible.
2. The inoculated plots increased yields, indicating a window of opportunity to change management. More reliance on BNF can be achieved and should therefore be explored more thoroughly. Depending on the implementation this could result in a large reduction of input costs, increased yields or both.
3. All but one trial plot yielding 10 tons per ha or more included some mineral N. Consequently Starter-N options should be explored.

6.1.2 *P.vulgaris* grown under hydroponics

1. Inoculation clearly increased nodulation, suggesting reliance on BNF can be increased.
2. Considering the negative outlier and the intensity of the growing system, caution should be taken though when implementing the technology. First a similar trial should be done in fresh, unused pumice to further evaluate the results of this experiment and the suitability of the medium. If this yields a positive response, a further sequence of tests may be done, for instance by a stepwise reduction the amount of N in the feeding solution.

6.2 Outgrower trials

1. The Legumefix treatments indicate inoculation will result in similar or improved yields of snow pea. Use of mineral fertilizers and hence related expenses can thus be reduced.
2. Consequently, profits and farm income can be increased by adoption of the technology.
3. Reliance on inoculation in sugar snap pea and garden pea should be further tested to see if the technology works for these varieties.

References

Anyango, B., Wilson, K. J., Beynon, J. L. & Giller, K. E. (1995) Diversity of rhizobia nodulating Phaseolus vulgaris L. in two Kenyan soils with contrasting pHs. *Applied and Environmental Microbiology,* **61,** 4016-4021.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E. & Thiombiano, L. (2006) African Soils: Their Productivity and Profitability of Fertilizer Use. *Background paper prepared for the African Fertiliser Summit*.

Bekunda, M., Sanginga, N. & Woomer, P. L. (2010) Restoring soil fertility in sub-sahara Africa. *Advances in Agronomy,* **108,** 183-236.

Bekunda, M. A., Bationo, A. & Ssali, H. (1997) Soil fertility management in Africa: A review of selected research trials. *In R.J. Buresh et al. (ed.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSSA, Madison, WI*, 63-79.

Bekunda, M. A., Nkonya, E., Mugendi, D. & Msaky, J. J. (2002) Soil fertility Status, Management, and research in East Africa. *East African Journal of Rural Development*.

Broughton, W. J., Hernández, G., Blair, M., Beebe, S., Gepts, P. & Vanderleyden, J. (2003) Beans (Phaseolus spp.) - Model food legumes. *Plant and Soil,* **252,** 55-128.

Chemining'wa, G. N., Muthomi, J. W. & Theuri, S. W. M. (2007) Effect of rhizobia inoculation and starter-N on nodulation, shoot biomass and yield of grain legumes. *Asian Journal of Plant Sciences,* **6,** 1113-1118.

Conway, G. & Toenniessen, G. (2003) Agriculture: Science for African food security. *Science,* **299,** 1187-1188.

FAO (2009) Global agriculture towards 2050. *How to Feed the World 2050 High Level Expert Forum*.

FAO (2011a) The State of Food Insecurity in the World.

FAO (2011b) The state of the worlds land and water resources for food and agriculture.

FAO (2012) Land Degradation. *SOLAW Thematic Report*.

Franke, A. C., Laberge, G., Oyewole, B. D. & Schulz, S. (2008) A comparison between legume technologies and fallow, and their effects on maize and soil traits, in two distinct environments of the West African savannah. *Nutrient Cycling in Agroecosystems,* **82,** 117-135.

Gilbert, N. (2012) African agriculture: Dirt poor. *Nature,* **483,** 525-527.

Giller, K. & Palm, C. (2004) Cropping systems: slash-and-burn cropping systems of the tropics. . *Encyclopedia of Plant and Crop Science*, 3.

Giller, K. E. (2001) *Nitrogen fixation in tropical cropping systems.* CAB Int, Wallingford.

Giller, K. E., Amijee, F., Brodrick, S. J. & Edje, O. T. (1998) Environmental constraints to nodulation and nitrogen fixation of Phaseolus vulgaris L. in Tanzania. II. Response to N and P fertilizers and inoculation with Rhizobium. *African Crop Science journal,* **6,** 171-178.

Giller, K. E. & Cadisch, G. (1995) Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil,* **174,** 255-277.

Hardarson, G. & Atkins, C. (2003) Optimising biological N2 fixation by legumes in farming systems. *Plant and Soil,* **252,** 41-54.

Jaetzold, R., Schmidt, H., Hornetz, B. & Shisanya, C. (2010) *Farm Management Handbook of Kenya.* Ministry of Agriculture, Kenya, in Cooperation with the German Agency for Technical Cooperation (GTZ), Nairobi.

Kaizzi, K. C., Byalebeka, J., Semalulu, O., Alou, I. N., Zimwanguyizza, W., Nansamba, A., Odama, E., Musinguzi, P., Ebanyat, P., Hyuha, T., Kasharu, A. K. & Wortmann, C. S. (2012) Optimizing smallholder returns to fertilizer use: Bean, soybean and groundnut. *Field Crops Research,* **127,** 109-119.

Kaschuk, G., Hungria, M., Andrade, D. S. & Campo, R. J. (2006) Genetic diversity of rhizobia associated with common bean (Phaseolus vulgaris L.) grown under no-tillage and conventional systems in Southern Brazil. *Applied Soil Ecology,* **32,** 210-220.

Kaschuk, G., Kuyper, T. W., Leffelaar, P. A., Hungria, M. & Giller, K. E. (2009) Are the rates of photosynthesis stimulated by the carbon sink strength of rhizobial and arbuscular mycorrhizal symbioses? *Soil Biology and Biochemistry,* **41,** 1233-1244.

Kipkoech, A., Okiror, M. A., Okalebo, J. R. & Maritim, H. K. (2007) Production efficiency and economic potential of different soil fertility management strategies among groundnut farmers of Kenya. *Science World Journal,* **2.**

Mugabe, J. (1994) Research on Biofertilizers: Kenya, Zimbabwe and Tanzania. *Biotechnology and Development Monitor,* **18,** 9-10.

Ndakidemi, P. A., Bambara, S. & Makoi, J. H. J. R. (2011) Micronutrient uptake in common bean (*Phaseolus vulgaris* L.) as affected by *Rhizobium* inoculation, and the supply of molybdenum and lime. *Plant OMICS,* **4,** 40-52.

Odame, H. (1997) Biofertilizer in Kenya: Research, production and extension dilemmas. *Biotechnology and Development Monitor,* **30,** 2023.

Okalebo, J. R., Othieno, C. O., Woomer, P. L., Karanja, N. K., Semoka, J. R. M., Bekunda, M. A., Mugendi, D. N., Muasya, R. M., Bationo, A. & Mukhwana, E. J. (2006) Available technologies to replenish soil fertility in East Africa. *Nutrient Cycling in Agroecosystems,* **76,** 153-170.

Peoples, M. B., Faizah, A. W., Rerkasem, B. & Herridge, D. (1989) *Methods for Evaluating Nitrogen Fixation by Nodulated Legumes in the Field.* ACIAR Monograph.

Sanchez, P. A. (2002) Soil fertility and hunger in Africa. *Science,* **295,** 2019-2020.

Sanchez, P. A., Shepherd, K. D., Soule, M., Place, F., Mokwunye, A., Buresh, R., Kwesiga, F., Izac, A.-M., Ndiritu, C. & Woomer, P. (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. *In R.J. Buresh et al. (ed.) Replenishing soil fertility in Africa. SSSA Spec. Pub. 51. SSSA, Madison, WI***,** 1-46.

Smaling, E., Nandwa, S. & Janssen, B. (1997) Soil fertility in Africa is at stake. *In R.J. Buresh et al. (ed.) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51. SSSA, Madison,WI***,** 47-61.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C. & Giller, K. E. (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems and Environment,* **110,** 149-165.

Tittonell, P. G., K. (2012) When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research,* **Article in press**.

WFP (2011) 2010 Food aid flows.

World_Bank (2011) *Africa development indicators 2011.*

Appendices

I. Climatic data Longonot

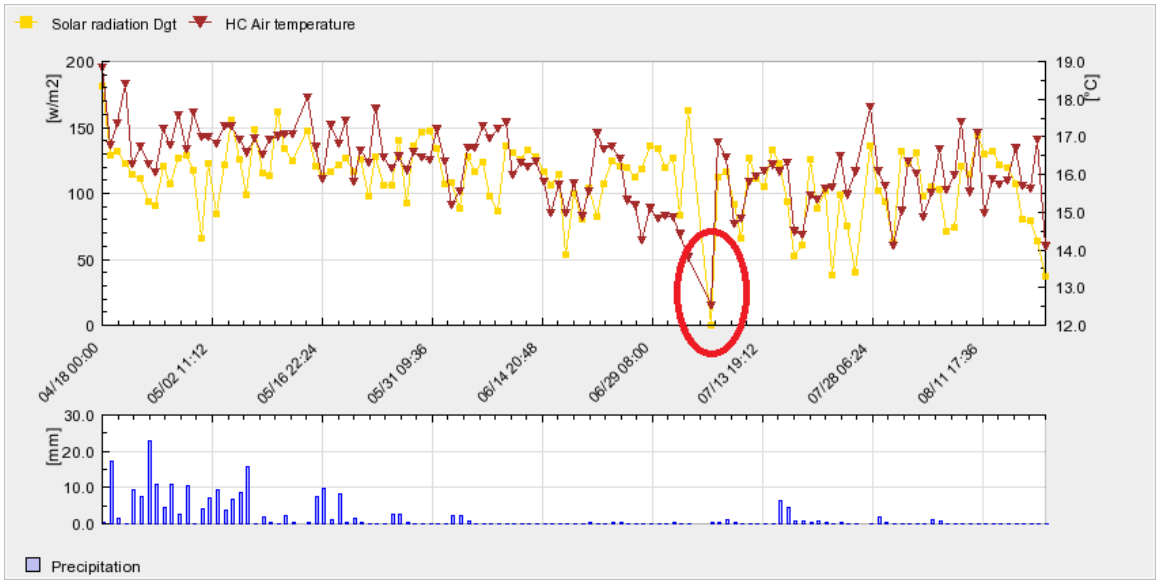


Figure 21 Solar radiation, HC Air temperature and precipitation collected from the farm weather station. Encircled in red missing data at the time of hailstorm. Heavy weather may have resulted in breakage of the equipment.

II. ANOVA emergence *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	1.815	0.605	0.12	
Block.Whole_plot stratum					
I	2	4.019	2.009	0.41	0.681
Residual	6	29.463	4.910	1.81	
Block.Whole_plot.Sub_plot stratum					
N	2	8.130	4.065	1.50	0.230
P	2	5.574	2.787	1.03	0.363
I.N	4	1.481	0.370	0.14	0.968
I.P	4	15.704	3.926	1.45	0.227
N.P	4	5.259	1.315	0.48	0.747
I.N.P	8	30.630	3.829	1.41	0.206
Residual	72	195.222	2.711		
Total	107	297.296			

Tables of means

Grand mean 95.

I	Legumefix	Biofix	Control
	95.	95.	96.

N	0	30	60
	96.	95.	95.

P	0	15	30
	95.	96.	95.

I	N	0	30	60
Legumefix		96.	95.	95.
Biofix		96.	95.	95.
Control		96.	95.	95.

I	P	0	15	30
Legumefix		95.	96.	95.
Biofix		95.	95.	96.
Control		96.	96.	95.

N	P	0	15	30
0		95.	96.	96.
30		95.	95.	95.
60		95.	96.	95.

I	N	P	0	15	30
Legumefix	0		95.	96.	96.
	30		94.	95.	95.
	60		95.	96.	94.
Biofix	0		95.	95.	96.
	30		94.	95.	95.

```
                    60                 96.       94.       96.
     Control         0                 96.       96.       96.
                    30                 96.       95.       96.
                    60                 94.       97.       94.
```

Standard errors of differences of means

```
Table                              I             N             P             I
                                                                             N
rep.                              36            36            36            12
s.e.d.                           0.5           0.4           0.4           0.8
d.f.                               6            72            72         24.12
Except when comparing means with the same level(s) of
I                                                                          0.7
d.f.                                                                        72

Table                              I             N             I
                                   P             P             N
                                                               P
rep.                              12            12             4
s.e.d.                           0.8           0.7           1.2
d.f.                           24.12            72         67.05
Except when comparing means with the same level(s) of
I                                0.7                         1.2
d.f.                              72                          72
I.N                                                          1.2
d.f.                                                          72
I.P                                                          1.2
d.f.                                                          72
```

III. ANOVA establishment *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	11981.	3994.	0.57	
Block.Whole_plot stratum					
I	2	7551.	3775.	0.54	0.611
Residual	6	42239.	7040.	3.40	
Block.Whole_plot.Sub_plot stratum					
N	2	12677.	6339.	3.06	0.053
P	2	3959.	1980.	0.96	0.389
I.N	4	26245.	6561.	3.17	0.019
I.P	4	10866.	2716.	1.31	0.274
N.P	4	13631.	3408.	1.65	0.172
I.N.P	8	8708.	1088.	0.53	0.834
Residual	72	149128.	2071.		
Total	107	286984.			

Tables of means

Grand mean 84.

I	Legumefix	Biofix	Control
	85.	82.	86.

N	0	30	60
	82.	84.	87.

P	0	15	30
	86.	83.	84.

I	N	0	30	60
Legumefix		81.	88.	86.
Biofix		76.	83.	88.
Control		89.	82.	88.

I	P	0	15	30
Legumefix		88.	82.	85.
Biofix		84.	78.	84.
Control		86.	89.	84.

N	P	0	15	30
0		88.	78.	80.
30		82.	85.	86.
60		88.	86.	87.

I	N	P	0	15	30
Legumefix	0		90.	73.	78.
	30		87.	89.	88.
	60		85.	83.	89.
Biofix	0		81.	68.	78.
	30		81.	81.	86.

	60	90.	85.	89.
Control	0	91.	93.	84.
	30	78.	83.	84.
	60	90.	91.	84.

Standard errors of differences of means

Table	I	N	P	I N
rep.	36	36	36	12
s.e.d.	4.1	2.2	2.2	5.2
d.f.	6	72	72	14.71
Except when comparing means with the same level(s) of				
I				3.9
d.f.				72

Table	I P	N P	I N P
rep.	12	12	4
s.e.d.	5.2	3.9	7.5
d.f.	14.71	72	46.17
Except when comparing means with the same level(s) of			
I	3.9		6.7
d.f.	72		72
I.N			6.7
d.f.			72
I.P			6.7
d.f.			72

IV. ANOVA nodulation *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	14.7539	4.9180	21.36	
Block.Whole_plot stratum					
I	2	4.9727	2.4864	10.80	0.010
Residual	6	1.3812	0.2302	0.98	
Block.Whole_plot.Sub_plot stratum					
N	2	9.9295	4.9648	21.17	<.001
P	2	0.7135	0.3567	1.52	0.225
I.N	4	0.7433	0.1858	0.79	0.534
I.P	4	1.9223	0.4806	2.05	0.097
N.P	4	1.3128	0.3282	1.40	0.243
I.N.P	8	1.2274	0.1534	0.65	0.730
Residual	72	16.8858	0.2345		
Total	107	53.8423			

Tables of means

Grand mean 2.64

I	Legumefix	Biofix	Control
	2.92	2.39	2.61

N	0	30	60
	3.04	2.58	2.30

P	0	15	30
	2.62	2.75	2.56

I	N	0	30	60
Legumefix		3.29	2.78	2.68
Biofix		2.71	2.38	2.10
Control		3.11	2.60	2.13

I	P	0	15	30
Legumefix		2.68	3.13	2.94
Biofix		2.35	2.57	2.26
Control		2.82	2.56	2.46

N	P	0	15	30
0		3.14	3.21	2.76
30		2.53	2.72	2.50
60		2.18	2.32	2.40

I	N	P	0	15	30
Legumefix	0		3.29	3.71	2.88
	30		2.54	2.96	2.83
	60		2.21	2.71	3.12
Biofix	0		2.79	2.88	2.46
	30		2.29	2.58	2.25

```
                      60              1.96     2.25     2.08
       Control         0              3.33     3.04     2.96
                      30              2.75     2.63     2.42
                      60              2.38     2.00     2.00
```

Standard errors of differences of means

```
Table                          I           N           P           I
                                                                   N
rep.                          36          36          36          12
s.e.d.                     0.113       0.114       0.114       0.197
d.f.                           6          72          72       41.13
Except when comparing means with the same level(s) of
I                                                              0.198
d.f.                                                              72

Table                          I           N           I
                               P           P           N
                                                       P
rep.                          12          12           4
s.e.d.                     0.197       0.198       0.342
d.f.                       41.13          72       76.87
Except when comparing means with the same level(s) of
I                          0.198                   0.342
d.f.                          72                      72
I.N                                                0.342
d.f.                                                  72
I.P                                                0.342
d.f.                                                  72
```

V. ANOVA yield *P.vulgaris* field trial

```
Source of variation                  d.f.         s.s.         m.s.      v.r.    F pr.

Block stratum                           3    20161023.     6720341.      2.95

Block.Whole_plot stratum
I                                       2    21441202.    10720601.      4.70    0.059
Residual                                6    13674838.     2279140.      0.87

Block.Whole_plot.Sub_plot stratum
N                                       2    11307100.     5653550.      2.17    0.122
P                                       2    11800388.     5900194.      2.26    0.112
I.N                                     4     9387168.     2346792.      0.90    0.469
I.P                                     4    13382341.     3345585.      1.28    0.285
N.P                                     4    10050279.     2512570.      0.96    0.433
I.N.P                                   8    23604067.     2950508.      1.13    0.353
Residual                               72   187839708.     2608885.

Total                                 107   322648113.
```

Tables of means

```
 Grand mean  7962.

          I   Legumefix       Biofix      Control
                  8512.        7954.        7421.

          N           0           30           60
                  7542.        8015.        8330.

          P           0           15           30
                  8228.        8162.        7496.

          I           N            0           30           60
  Legumefix                    7781.        9077.        8678.
     Biofix                    7450.        7920.        8491.
    Control                    7396.        7047.        7820.

          I           P            0           15           30
  Legumefix                    9471.        8294.        7771.
     Biofix                    7829.        8326.        7707.
    Control                    7385.        7866.        7011.

          N           P            0           15           30
          0                    7867.        7217.        7543.
         30                    8189.        8367.        7488.
         60                    8628.        8903.        7458.

          I           N            P            0           15           30
  Legumefix           0                     8720.        7078.        7547.
                     30                    10271.        8558.        8402.
                     60                     9422.        9246.        7366.
     Biofix           0                     7127.        6697.        8525.
                     30                     7826.        8487.        7448.
```

```
                   60            8533.     9794.     7146.
      Control       0            7755.     7876.     6557.
                   30            6469.     8056.     6615.
                   60            7930.     7667.     7862.
```

Standard errors of differences of means

```
Table                          I             N             P             I
                                                                         N
rep.                          36            36            36            12
s.e.d.                     355.8         380.7         380.7         645.4
d.f.                           6            72            72         45.18
Except when comparing means with the same level(s) of
I                                                                    659.4
d.f.                                                                    72

Table                          I             N             I
                               P             P             N
                                                           P
rep.                          12            12             4
s.e.d.                     645.4         659.4        1134.1
d.f.                       45.18            72         77.49
Except when comparing means with the same level(s) of
I                          659.4                      1142.1
d.f.                          72                          72
I.N                                                   1142.1
d.f.                                                      72
I.P                                                   1142.1
d.f.                                                    72
```

VI. ANOVA biomass *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	3.708E+08	1.236E+08	4.75	
Block.Whole_plot stratum					
I	2	2.708E+07	1.354E+07	0.52	0.619
Residual	6	1.560E+08	2.600E+07	2.27	
Block.Whole_plot.Sub_plot stratum					
N	2	1.057E+08	5.287E+07	4.61	0.013
P	2	1.328E+07	6.639E+06	0.58	0.563
I.N	4	5.397E+07	1.349E+07	1.18	0.328
I.P	4	4.753E+07	1.188E+07	1.04	0.395
N.P	4	8.246E+06	2.062E+06	0.18	0.948
I.N.P	8	5.686E+07	7.107E+06	0.62	0.758
Residual	72	8.256E+08	1.147E+07		

Total 107 1.665E+09

Tables of means

Grand mean 17295.

I	Legumefix	Biofix	Control
	17565.	16593.	17727.

N	0	30	60
	16063.	17336.	18486.

P	0	15	30
	17359.	17689.	16837.

I	N	0	30	60
Legumefix		16875.	17163.	18657.
Biofix		13984.	17271.	18524.
Control		17331.	17573.	18277.

I	P	0	15	30
Legumefix		18146.	16945.	17603.
Biofix		15833.	17360.	16585.
Control		18099.	18760.	16322.

N	P	0	15	30
0		16602.	15995.	15593.
30		17262.	17908.	16837.
60		18214.	19163.	18081.

I	N	P	0	15	30
Legumefix	0		18432.	14967.	17226.
	30		16310.	17511.	17667.

```
                    60              19696.    18358.    17917.
      Biofix         0              14147.    14770.    13035.
                    30              16236.    18558.    17018.
                    60              17116.    18753.    19704.
     Control         0              17226.    18248.    16519.
                    30              19241.    17654.    15825.
                    60              17829.    20378.    16623.
```

Standard errors of differences of means

```
Table                              I            N            P            I
                                                                          N
rep.                              36           36           36           12
s.e.d.                        1201.9        798.1        798.1       1648.8
d.f.                               6           72           72        19.96
Except when comparing means with the same level(s) of
I                                                                    1382.4
d.f.                                                                     72

Table                              I            N            I
                                   P            P            N
                                                             P
rep.                              12           12            4
s.e.d.                        1648.8       1382.4       2557.5
d.f.                           19.96           72        60.38
Except when comparing means with the same level(s) of
I                             1382.4                    2394.4
d.f.                              72                        72
I.N                                                     2394.4
d.f.                                                        72
I.P                                                     2394.4
d.f.                                                        72
```

VII. ANOVA yield per plant *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.00005422	0.00001807	0.30	
Block.Whole_plot stratum					
I	2	0.00093542	0.00046771	7.64	0.022
Residual	6	0.00036748	0.00006125	2.77	
Block.Whole_plot.Sub_plot stratum					
N	2	0.00008603	0.00004302	1.94	0.151
P	2	0.00002265	0.00001133	0.51	0.602
I.N	4	0.00011613	0.00002903	1.31	0.274
I.P	4	0.00005516	0.00001379	0.62	0.648
N.P	4	0.00013043	0.00003261	1.47	0.220
I.N.P	8	0.00038780	0.00004847	2.19	0.038
Residual	72	0.00159454	0.00002215		
Total	107	0.00374986			

Tables of means

Grand mean 0.025

I	Legumefix	Biofix	Control
	0.028	0.026	0.021

N	0	30	60
	0.024	0.025	0.026

P	0	15	30
	0.026	0.025	0.024

I	N	0	30	60
Legumefix		0.025	0.030	0.028
Biofix		0.026	0.025	0.027
Control		0.020	0.020	0.023

I	P	0	15	30
Legumefix		0.030	0.027	0.027
Biofix		0.026	0.026	0.026
Control		0.021	0.021	0.021

N	P	0	15	30
0		0.023	0.023	0.025
30		0.026	0.025	0.024
60		0.027	0.027	0.024

I	N	P	0	15	30
Legumefix	0		0.024	0.025	0.027
	30		0.036	0.025	0.028
	60		0.029	0.031	0.025
Biofix	0		0.025	0.023	0.030

	30	0.025	0.027	0.024
	60	0.028	0.029	0.024
Control	0	0.021	0.020	0.020
	30	0.017	0.023	0.020
	60	0.023	0.021	0.023

Standard errors of differences of means

Table	I	N	P	I N
rep.	36	36	36	12
s.e.d.	0.0018	0.0011	0.0011	0.0024
d.f.	6	72	72	17.07
Except when comparing means with the same level(s) of				
I				0.0019
d.f.				72

Table	I P	N P	I N P
rep.	12	12	4
s.e.d.	0.0024	0.0019	0.0036
d.f.	17.07	72	53.57
Except when comparing means with the same level(s) of			
I	0.0019		0.0033
d.f.	72		72
I.N			0.0033
d.f.			72
I.P			0.0033
d.f.			72

VIII. ANOVA plant density *P.vulgaris* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	2.895E+10	9.651E+09	3.70	
Block.Whole_plot stratum					
I	2	5.552E+10	2.776E+10	10.66	0.011
Residual	6	1.563E+10	2.605E+09	1.14	
Block.Whole_plot.Sub_plot stratum					
N	2	1.372E+08	6.861E+07	0.03	0.971
P	2	8.285E+09	4.143E+09	1.81	0.172
I.N	4	5.379E+09	1.345E+09	0.59	0.673
I.P	4	5.027E+09	1.257E+09	0.55	0.701
N.P	4	3.078E+09	7.695E+08	0.34	0.853
I.N.P	8	1.399E+10	1.748E+09	0.76	0.637
Residual	72	1.651E+11	2.293E+09		

Total 107 3.011E+11

Tables of means

Variate: plant_densityplants/ha

Grand mean 325069.

I	Legumefix	Biofix	Control
	311312.	306865.	357030.

N	0	30	60
	324287.	326663.	324257.

P	0	15	30
	331171.	331354.	312683.

I	N	0	30	60
Legumefix		314967.	312409.	306561.
Biofix		292398.	314053.	314145.
Control		365497.	353527.	352065.

I	P	0	15	30
Legumefix		327577.	309028.	297332.
Biofix		303088.	315333.	302175.
Control		362847.	369700.	338542.

N	P	0	15	30
0		340552.	324836.	307474.
30		325567.	335344.	319079.
60		327394.	333882.	311495.

I	N	P	0	15	30
Legumefix	0		358827.	289200.	296875.

```
                     30          297149.   338268.   301809.
                     60          326754.   299616.   293311.
      Biofix          0          292215.   295504.   289474.
                     30          311952.   313322.   316886.
                     60          305099.   337171.   300164.
     Control          0          370614.   389803.   336075.
                     30          367599.   354441.   338542.
                     60          350329.   364857.   341009.
```

Standard errors of differences of means

```
Table                                I             N             P             I
                                                                               N
rep.                                36            36            36            12
s.e.d.                         12030.0       11286.8       11286.8       19987.6
d.f.                                 6            72            72         36.34
Except when comparing means with the same level(s) of
I                                                                        19549.3
d.f.                                                                          72

Table                                I             N             I
                                     P             P             N
                                                                 P
rep.                                12            12             4
s.e.d.                         19987.6       19549.3       34115.3
d.f.                             36.34            72         75.61
Except when comparing means with the same level(s) of
I                              19549.3                     33860.3
d.f.                                72                          72
I.N                                                        33860.3
d.f.                                                            72
I.P                                                        33860.3
d.f.                                                            72
```

IX. ANOVA total plant N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	17530.	5843.	1.06	
Block.Whole_plot stratum					
I	2	12802.	6401.	1.16	0.375
Residual	6	33113.	5519.	2.36	
Block.Whole_plot.Sub_plot stratum					
N	2	6989.	3495.	1.49	0.232
P	2	90.	45.	0.02	0.981
I.N	4	11947.	2987.	1.28	0.287
I.P	4	7701.	1925.	0.82	0.515
N.P	4	8214.	2054.	0.88	0.482
I.N.P	8	15165.	1896.	0.81	0.596
Residual	72	168538.	2341.		
Total	107	282091.			

Tables of means

Grand mean 174.1

I	Legumefix	Biofix	Control
	183.9	159.0	179.5

N	0	30	60
	168.0	168.9	185.5

P	0	15	30
	174.2	175.2	173.0

I	N	0	30	60
Legumefix		170.3	181.4	200.1
Biofix		140.1	156.9	179.9
Control		193.6	168.5	176.5

I	P	0	15	30
Legumefix		193.8	171.5	186.5
Biofix		153.0	160.3	163.6
Control		175.8	193.9	168.9

N	P	0	15	30
0		180.1	158.5	165.4
30		164.9	165.9	175.9
60		177.6	201.3	177.6

I	N	P	0	15	30
Legumefix	0		210.7	130.6	169.6
	30		170.9	174.6	198.8
	60		199.7	209.4	191.2

```
      Biofix          0            146.5     147.4     126.5
                     30            144.7     156.0     169.9
                     60            167.9     177.5     194.3
     Control          0            183.0     197.4     200.2
                     30            179.2     167.2     159.1
                     60            165.2     217.0     147.3
```

Standard errors of differences of means

```
Table                              I            N            P            I
                                                                          N
rep.                              36           36           36           12
s.e.d.                         17.51        11.40        11.40        23.81
d.f.                               6           72           72        19.34
Except when comparing means with the same level(s) of
I                                                                     19.75
d.f.                                                                     72

Table                              I            N            I
                                   P            P            N
                                                             P
rep.                              12           12            4
s.e.d.                         23.81        19.75        36.70
d.f.                           19.34           72        59.10
Except when comparing means with the same level(s) of
I                              19.75                     34.21
d.f.                              72                        72
I.N                                                      34.21
d.f.                                                        72
I.P                                                      34.21
d.f.                                                        72
```

X. ANOVA log(Nodulation score) *P.sativum* field trial

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	3	0.24743	0.08248	1.05	
Block.Whole_plot stratum					
I	2	0.40746	0.20373	2.59	0.154
Residual	6	0.47147	0.07858	6.38	
Block.Whole_plot.Sub_plot stratum					
N	2	0.09801	0.04900	3.98	0.023
P	2	0.02260	0.01130	0.92	0.404
I.N	4	0.02856	0.00714	0.58	0.678
I.P	4	0.09032	0.02258	1.83	0.132
N.P	4	0.01189	0.00297	0.24	0.914
I.N.P	8	0.09579	0.01197	0.97	0.464
Residual	72	0.88614	0.01231		
Total	107	2.35965			

Tables of means

Grand mean 0.61

I	+I1	+I2	0
	0.50	0.65	0.69

N	0	30	60
	0.56	0.66	0.62

P	0	15	30
	0.65	0.59	0.60

I	N	0	30	60
+I1		0.45	0.52	0.54
+I2		0.59	0.74	0.63
0		0.64	0.73	0.68

I	P	0	15	30
+I1		0.48	0.54	0.49
+I2		0.68	0.59	0.69
0		0.78	0.64	0.64

N	P	0	15	30
0		0.59	0.55	0.54
30		0.69	0.64	0.66
60		0.66	0.58	0.61

I	N	P	0	15	30
+I1	0		0.50	0.45	0.40

	30	0.42	0.63	0.51
	60	0.53	0.53	0.56
+I2	0	0.55	0.55	0.68
	30	0.84	0.63	0.74
	60	0.66	0.60	0.64
0	0	0.73	0.66	0.55
	30	0.80	0.67	0.73
	60	0.80	0.60	0.63

Standard errors of differences of means

Table	I	N	P	I N
rep.	36	36	36	12
s.e.d.	0.083	0.034	0.034	0.096
d.f.	6	72	72	10.76
Except when comparing means with the same level(s) of				
I				0.059
d.f.				72

Table	I P	N P	I N P
rep.	12	12	4
s.e.d.	0.096	0.059	0.127
d.f.	10.76	72	29.41
Except when comparing means with the same level(s) of			
I	0.059		0.103
d.f.	72		72
I.N			0.103
d.f.			72
I.P			0.103
d.f.			72

XI. ANOVA yield *P.sativum* field trial

```
Source of variation                d.f.        s.s.        m.s.      v.r.    F pr.

Block stratum                        3     8471273.    2823758.     0.70

Block.Whole_plot stratum
I                                    2     9277174.    4638587.     1.16    0.376
Residual                             6    24074661.    4012444.     2.33

Block.Whole_plot.Sub_plot stratum
N                                    2     5723639.    2861820.     1.66    0.197
P                                    2     3892335.    1946168.     1.13    0.329
I.N                                  4     9371620.    2342905.     1.36    0.257
I.P                                  4    11560362.    2890091.     1.68    0.165
N.P                                  4     9123783.    2280946.     1.32    0.270
I.N.P                                8    17516542.    2189568.     1.27    0.273
Residual                            72   124160403.    1724450.

Total                              107   223171793.
```

Tables of means

```
Grand mean  6771.

         I        +I1        +I2          0
               6400.      7116.      6798.

         N          0         30         60
               6530.      6703.      7081.

         P          0         15         30
               6867.      6506.      6941.

         I          N          0         30         60
       +I1                 6179.      6817.      6203.
       +I2                 6749.      6842.      7757.
         0                 6662.      6450.      7283.

         I          P          0         15         30
       +I1                 6442.      6014.      6742.
       +I2                 7237.      6439.      7671.
         0                 6922.      7065.      6408.

         N          P          0         15         30
         0                 6844.      6202.      6545.
        30                 6267.      6847.      6995.
        60                 7491.      6470.      7283.

         I          N          P          0         15         30
       +I1          0                 6671.      5311.      6554.
                   30                 5993.      7212.      7246.
                   60                 6662.      5519.      6428.
```

```
     +I2       0             7208.     6468.     6571.
              30             7124.     5914.     7487.
              60             7379.     6936.     8956.
       0       0             6652.     6826.     6509.
              30             5682.     7416.     6251.
              60             8431.     6954.     6465.
```

Standard errors of differences of means

```
Table                            I           N           P           I
                                                                     N
rep.                            36          36          36          12
s.e.d.                       472.1       309.5       309.5       643.8
d.f.                             6          72          72       19.54
Except when comparing means with the same level(s) of
I                                                                536.1
d.f.                                                                72

Table                            I           N           I
                                 P           P           N
                                                         P
rep.                            12          12           4
s.e.d.                       643.8       536.1       994.7
d.f.                         19.54          72       59.54
Except when comparing means with the same level(s) of
I                            536.1                   928.6
d.f.                            72                      72
I.N                                                  928.6
d.f.                                                    72
I.P                                                  928.6
d.f.                                                    72
```

XII. ANOVA nodulation Runner beans trial

```
Source of variation              d.f.        s.s.        m.s.     v.r.   F pr.

Whole_plot stratum
Perkla.I                            1      0.0156      0.0156

Whole_plot.Sub_plot stratum
Perkla                              1      0.5017      0.5017     1.74   0.214
I                                   1      0.9184      0.9184     3.18   0.102
Perkla.I                            1      0.3617      0.3617     1.25   0.287
Residual                           11      3.1730      0.2885

Total     15      4.9705
```

Tables of means

```
 Grand mean  2.34

          I      Control   Legumefix
                    2.10        2.58

     Perkla          250         500
                    2.17        2.52

          I       Perkla         250         500
    Control                     2.10        2.11
  Legumefix                     2.23        2.93
```

Standard errors of differences of means

```
Table                             I        Perkla           I
                                                       Perkla
rep.                              8             8           4
d.f.                             11            11          11
s.e.d.                        0.269         0.269       0.380
Except when comparing means with the same level(s) of
I                                                       0.410
Perkla                                                  0.410
```

XIII. ANOVA nodulation runner beans trial without outliers

```
Source of variation                 d.f.  (m.v.)        s.s.        m.s.     v.r.   F pr.

Whole_plot stratum
Perkla.I                               1            0.02309     0.02309

Whole_plot.Sub_plot stratum
Perkla                                 1            0.00309     0.00309     0.05   0.836
I                                      1            2.59564     2.59564    38.16   <.001
Perkla.I                               1            0.34321     0.34321     5.05   0.051
Residual                               9     (2)    0.61220     0.06802

Total     13      (2)      3.26984
```

Tables of means

```
 Grand mean  2.35

         I       Control    Legumefix
                    1.95         2.75

    Perkla          250          500
                   2.34         2.36

           I      Perkla          250          500
     Control                     2.10         1.79
   Legumefix                     2.57         2.94
```

Standard errors of differences of means

```
Table                           I            Perkla              I
                                                            Perkla
rep.                            8                 8              4
d.f.                            9                 9              9
s.e.d.                      0.130             0.130          0.184
Except when comparing means with the same level(s) of
I                                                            0.199
Perkla                                                       0.199
```

XIV. ANOVA outgrowers yields excluding sugar snap pea

```
Source of variation          d.f.  (m.v.)      s.s.        m.s.     v.r.   F pr.

Farmer stratum                  9     (8)  141042000.   15671333.   13.43

Farmer.*Units* stratum
Plot                            1           20037630.   20037630.   17.17  0.003
Residual                        9     (8)   10505680.    1167298.

Total                          19    (16)  162678000.
```

Tables of means

```
 Grand mean  5670.

        Plot          N          R
                  4924.      6416.
```

Standard errors of differences of means

```
Table                        Plot
rep.                           18
d.f.                            9
s.e.d.     360.1
```

XV. ANOVA outgrowers yields excluding sugar snap pea, excluding outliers

```
Source of variation          d.f.  (m.v.)         s.s.         m.s.     v.r.   F pr.

Farmer stratum                  7    (10)    24790000.     3541429.     3.93

Farmer.*Units* stratum
Plot                            1            34219037.    34219037.    37.96   <.001
Residual                        7    (10)     6310000.      901429.

Total                          15    (20)    46310000.
```

Tables of means

```
 Grand mean  6875.

        Plot          N          R
                  5900.      7850.
```

Standard errors of differences of means

```
Table                     Plot
rep.                        18
d.f.                         7
s.e.d.                   316.5
```

XVI. Outgrower yields

Table 16 Outgrower yields

Farmer	Crop	Yield R (kg/ha)	Yield N (kg/ha)
Japhet Bundi	Snow pea	8200	7000
David munene	Sugar snap	8000	8800
Daniel Muriki	Garden pea	-	-
Eric Mutwiri	Snow pea	4400	4800
Antony Waituika	Garden pea	-	-
Solomon Kimonye	Snow pea	8000	4800
David Kimathi	Snow pea	7600	6000
Amariah Kiende	Garden pea	-	-
Julius Kiburi	Snow pea	6000	4800
Joseph Karemu	Snow pea	10000	6400
Francis Mwarano	Snow pea	9000	7000
Isaac Kihara	Snow pea	-	-
Isaac Kamau	Snow pea	10000	6400
Gerald Gichuki	Snow pea	9600	6400
Kabugu kamanga	Sugar snap	-	-
Patricia Njeri	Snow pea	-	-
Joseph Murithi	Snow pea	840	1160
Njeri Wangechi	Snow pea	520	880