The SAFERNAC model: Evaluation, calibration and application for nutrient management in Rwandan coffee fields

MSc Thesis Plant Production Systems

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Contact office.pp@wur.nl for access to data, models and scripts used for the analysis

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Summary

Continuous coffee growing without adequate nutrient replenishment can lead to depletion of soil nutrient stocks endangering the income security of Rwandan coffee growers. Determining nutrient requirements to meet growth demand depends on the indigenous soil supply and requires a balanced approach. The SAFERNAC model is a potentially useful tool in the development of a fertilization plan, but after its development in Tanzania, it has not been tested in other conditions.

This study aimed to explore fertilization options with the SAFERNAC model at hand. To this end, the model was first evaluated and calibrated to the local conditions. Then it was used to assess common nutrient management practices for coffee in Rwanda, in comparison to blanket recommendations and to the in-situ production of mulch through Tephrosia and coffee intercropping.

The predictive ability of SAFERNAC was found insufficient due to lack of accuracy and precision. Levels of soil exchangeable K were much lower in the Rwandan testing fields in comparison to the Tanzanian region where SAFERNAC was developed. The model was calibrated on these conditions using data of the intercropped plots, however its accuracy remained low. Possible reasons were the measurement error of the soil chemical fertility or nutrient input data, or the model structure that fails to capture the K dynamics in the crop – soil system.

Due to the model inaccuracy, exact fertilizer recommendations were not of practical use. However, common practices were shown to be inefficient and ineffective, either due to imbalanced nutrient addition or inadequate quantities. Finally, the need for site-specific planning was identified due to variation in the inherent soil fertility.

Concluding, the SAFERNAC model needs to further be tested with good quality data to identify its potential. Better understanding of the nutrient soil pools, particularly K, and the uptake processes by the coffee are needed to determine the necessary adjustments to the model's parameters and structure.

Keywords: SAFERNAC model, coffee, model evaluation, model calibration, nutrient management, K limitation

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"*The more I learn, the more I realize how much I don't know*" (Albert Einstein)

Elpida Theodosiadou
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Table of Abbreviations

Abbreviation	Explanation
SAFERNAC	Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee
QUEFTS	Quantitative Evaluation of the Fertility of Tropical Soils
RSG	Reference Soil Group
NAEB	National Agricultural Export Development Board
Y_{max}	Potential coffee yield
N	Nitrogen
P	Phosphorus
K	Potassium
SOC	Soil organic carbon
TN	Total soil Nitrogen
P-Bray-I	Plant available P analyzed with Bray-I method
P-Olsen	Plant available P analyzed with Olsen method
K-exch	Exchangeable K
RF	Regular fields
TP	Tephrosia plots
SN, SP, SK	Potential supplies of nutrients as calculated by the model
UN, UP, UK	Actual uptakes of nutrients as calculated by the model
B	Before the establishment of the Tephrosia
A	After the establishment of the Tephrosia
PhE_D	Maximum physiological efficiency (at dilution)
PhE_A	Minimum physiological efficiency (at accumulation)
RMSE	Root Mean Square Error
MSE_{sys}	Systematic Mean Square Error
MSE_{unsys}	Unsystematic Mean Square Error
RMSEP	Root Mean Square Error of Prediction

Introduction

Problem definition

Global coffee production in 2015/2016 was estimated at 8.8 million tons (International Coffee Organization, 2016a). Rwanda is amongst the top 40 coffee producers in the world (FAOSTAT, 2016) with total production of 15 thousand tons in 2015/2016 (International Coffee Organization, 2016b), which is almost 0.2% of the global market share. Local consumption is low (0.01 kg per capita per annum) (International Coffee Organization, 2016b), therefore, coffee is one of the country's main agricultural export commodities (FAO, 2016). In 2007 18% of total Rwandan exports was attributed to coffee (Malunda, 2012), produced by its 500,000 growers (Unknown, 2006). The most common cultivated species in Rwanda is *Coffea arabica* (Bote, 2016).

Currently the major constraint in the development of the coffee export sector in Rwanda is low and unstable coffee yields (Bucagu et al., 2013). Economic yield, i.e. the dry matter production of plant parts that can be used as economic products (Engels et al., 2011), is defined in coffee as "the quantity of coffee beans dried to 10 - 12% moisture per unit area of land" (Nair, 2010), also referred to as "parchment yield". Four agricultural zones of Rwanda (Fig. 1.1) have been classified as moderately to very suitable for growing coffee in terms of their climate, even though soil and topographic characteristics are not always favourable for its growth (Verdoodt and Ranst, 2003). According to Nzeyimana et al. (2013), yields vary considerably among different regions, between 0.8 and 1.6 tons/ha of dry coffee beans, with highest levels recorded in the West of the country (1.1 - 1.6 tons/ha), which has been classified as highly suitable. The maximum recorded yield is 2.8 tons/ha (Bucagu et al., 2013).

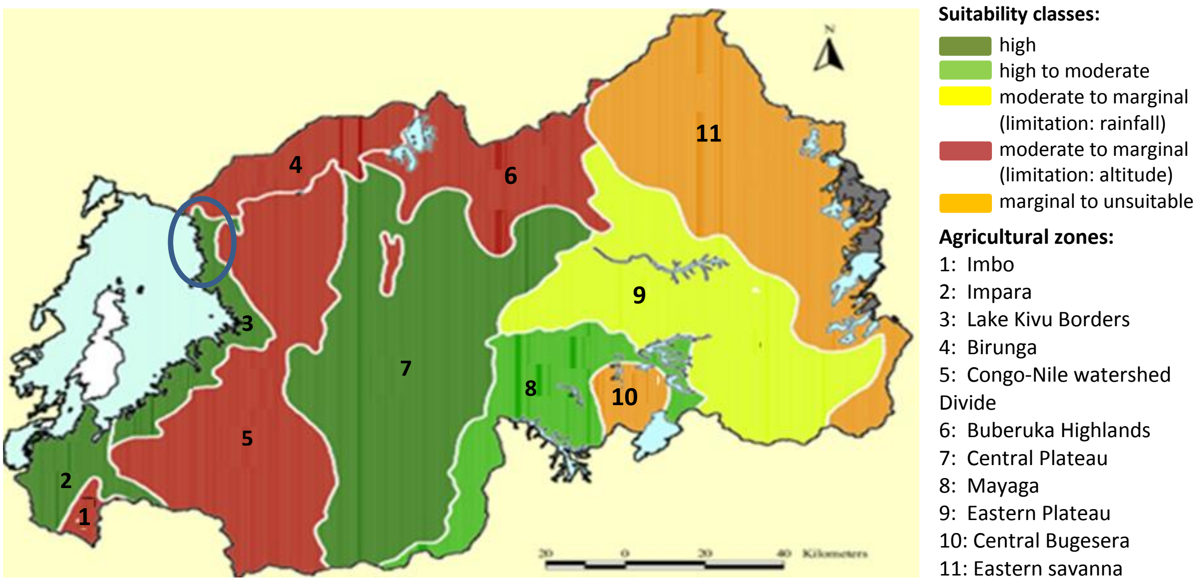


Figure 1.1. The agricultural zones of Rwanda and their suitability for coffee growing according to the climate. Source: (Verdoodt and Ranst, 2003)*. Blue circle indicates the location of the study region.*

This yield variability in Rwanda is mainly attributed to poor soil fertility, exacerbated by improper management. Soils where coffee is grown often lack important nutrients, like Ca, Mg, P, K, S, Zn and Bo (Nzeyimana et al., 2013), with N usually being the most limiting (Nair, 2010). Another common problem in coffee fields is low soil pH (even lower than 5.0), which might result in aluminium (Al) toxicity (Nzeyimana et al., 2013). The latter limits coffee root development and can lead to Ca and Mg deficiencies. Furthermore, due to the hilly topography of the country, soil erosion can occur, resulting in nutrient relocation and reduction of the soil depth (Nzeyimana et al., 2013).

Underlying problems of poor soil fertility are land scarcity and suboptimal application of good management practices (Appendix 1). Due to high population density, many smallholder growers, who depend on agriculture for their livelihoods, are forced to cultivate their fields continuously, leading to constant nutrient removal via the harvested product (Kwesiga et al., 2003), further reducing the fertility levels of the soils and compromising yields. Additionally, according to a survey among coffee farmers in Rwanda by Loverdige et al. (2002), 65.4% of the farmers interviewed mulch their coffee fields, only 12.9% use compost and 9.9% use chemical fertilizers. Reasons for not applying mulch were claimed to be unawareness about the necessity (65%), unavailability of materials (13% for manure and 21.8% for fertilizers), prioritizing other more important crops (8%), or inability to afford it (52.5%). About 77.5% of the farmers gather mulch from their own fields, while only 6.1% pay for all the mulch they use (Loveridge et al., 2002). According to Bucagu et al. (2013), at present, farmers use all the organic matter they can find as mulch for their coffee fields. Often, mulch is collected from food crop fields to be used in the coffee fields, which results in a reduction of the fertility of the food crop fields (Bucagu et al., 2013). Lack of available land also restricts the cultivation of plants that could be used as mulch (Nzeyimana et al., 2017). Others authors also report the access or high prices of fertilizers and organic materials, labour demands (Nzeyimana et al., 2013), or lack of farmer motivation to apply good management practices or knowledge about the benefits of nutrient inputs (Jassogne et al., 2013) as hindrances for coffee farming.

Other problems faced by the coffee sector in Rwanda are weather variability, like droughts (Unknown, 2010) and fluctuating coffee prices in the world market (Maro et al. 2014), resulting in further financial risks and discouragement from application of useful but costly management practices (Unknown, 2013).

Nutrient inputs

Covering yield gaps requires the implementation of a set of inputs within the specific physical and socio-economical context (van Ittersum and Rabbinge, 1997). Required inputs include seed, water, nutrients, but also labour or mechanisation and pesticides (van Ittersum and Rabbinge, 1997). This study will focus on nutrient inputs, as they appear to be the main limitation in Rwandan coffee farms.

Two main nutrient input types are inorganic fertilizers and organic sources. Artificial inputs in the form of inorganic fertilizers contain nutrients readily available to the plant. The blanket recommendations for coffee cultivation in Rwanda include application in two doses in March and September according to the following scheme (Nzeyimana et al., 2013): NPK: (20-10-10) 400 g per tree per year or NPK: (17-17-17) 120 g per tree per year and urea: (46%N) 75 g per tree per year. Others suggest three or four applications per year (Carr, 1993; Njoroge, 1985). Additionally, since soils in Rwanda are often acidic, Ca and Mg in the form of agricultural lime can also be applied to regulate the pH (Nzeyimana et al., 2013). This improves nutrient availability and helps prevent problems like aluminium toxicity.

Organic amendments commonly used in Rwanda are various grasses (Napier grass, *Panicum* spp., *Symbopogon* spp), crop residues, especially maize and bean stover, banana or sugarcane leaves, coffee prunings, Eucalyptus or Grevillea branches and leaves, sorghum thatches and animal manures (Jassogne et al., 2013; Nzeyimana et al., 2013). They are often applied in a mixture as mulch.

Organic materials are usually either bought or grown elsewhere, either on dedicated fields or field margins and are, as already mentioned, often hard to find or unaffordable for the coffee growers. An alternative, low-cost technology to maintain the productivity of farming systems is agroforestry (Kwesiga et al., 2003), a form of intercropping that involves a shrub or tree as the companion crop established within the main crop. It allows for in-situ production of organic materials through its regular coppicing and consequent application of the biomass as mulch or incorporation into the soil (Jassogne et al., 2013; Kwesiga et al., 2003). Leguminous species are commonly chosen, to profit from their N fixing ability to produce enriched materials which are returned to the soil with senescence, litter fall and prunings (Nair, 2010). Additional benefits derive from the ability of tree rooting systems to function as nutrient pumps from deeper soil layers (Nair, 2010), thus enhancing the internal nutrient recycling on the field. Finally, woody species can offer additional products, like timber or firewood.

Common trees used in agroforestry systems in the African Great Lake region are *Leucaena leucocephala*, *Calliandra calothyrsus*, *Tephrosia vogelii* and banana (Jassogne et al., 2013; Nzeyimana et al., 2013). Particularly, *T. vogelii* is one of the advised plants by the World Agroforestry Center (ICRAF), not only for soil improvement, but also for pest and weed management (Drechsel et al., 1996). Mulch from this shrub has been found to increase coffee yields, especially when in intercropping conditions (Bucagu et al., 2013).

Except for adding nutrients in the soil, mulching offers other, multiple advantages: reduces runoff and soil erosion; improves soil infiltration to maintain soil moisture; improves soil structure; reduces soil surface temperature and suppresses weeds (Nair, 2010). Especially in the hilly and sloping topography of Rwanda, in combination with high annual rainfall, mulching could be of high importance for soil conservation (Nzeyimana et al., 2017).

The apparent disadvantage of organic materials as nutrient sources is their varying composition and quality and the necessity to decompose first before the nutrients become available to the plant. The nutrient composition of plants is dependent on species, climate and soil nutrient supply during growth (Berg and McClaugherty, 2008). The amount of C, N, lignin and polyphenols in litter and their ratios are the most common chemical criteria used to define litter quality (Berg and McClaugherty, 2008). Organic sources commonly found in Sub-Saharan Africa are of low to medium quality (Vanlauwe and Giller, 2006). Input quality is important in crop nutrition, as it determines the amount of nutrients that will be available to the plants, but also the rate of the decomposition in time.

The decomposition rate depends on climate (temperature and rainfall), litter quality and microbial community (Couteaux et al., 1995) and involves a combination of biological, chemical and physical processes on a continuously changing substrate as some components decompose faster than others (Berg and McClaugherty, 2008). Thus, nutrients are released at different rates and with different patterns in time; either slowly but steadily, or very quickly and others are soon immobilized and become unavailable (Berg and McClaugherty, 2008). Consequently, while artificial fertilizers provide nutrients in a form that can be directly taken up by the plant, those from organic sources become gradually available to the crop.

Soil nutrient availability, crop requirements and uptake

The portion of added nutrients that eventually becomes available to the crop depends on several factors related to the plant, the soil and the environment (Marschner and Rengel, 2011). Main soil properties that affect nutrient availability are the moisture content, pH, microbial activity, cation exchange capacity, soil depth and structure and the soil organic matter (Marschner and Rengel, 2011). Depending on these properties, the applied nutrients will either be taken up, leached or immobilized. For example, availability of Mn, like other nutrients, is related to pH, as it determines its mobility (Berg and McClaugherty, 2008). Therefore, not all of the supplied nutrients will be available for uptake. Potential nutrient supply is defined as the "total quantity of a nutrient within the reach of roots that is, or becomes, available during crop growth from fertilizers and manures and by soil processes" (Janssen, 1998).

On the other side, crop nutrient requirements for growth and production depend on various factors, like its physiology, growth stage and environmental conditions, e.g. the level of shading (Bote, 2016). Demand is higher during the growth phase, which for coffee is after the long dry season (June-September). Lack of one or more nutrients will lead to deficiencies and finally in compromised yields (Rose and Bowden, 2013). In particular, lack of N limits vegetative growth, while P and K are important during the first years of establishment and for the development of the coffee beans (Nzeyimana et al., 2013). Other deficiencies commonly reported in coffee relate to Zn, Fe, Mn, S and B (Carr, 1993).

Eventually, the amount of a nutrient that will be taken up by the crop depends on the relative availability of other nutrients, based on the general principle of Liebig's law of the minimum. A minimum yield will be acquired even when no nutrient is applied. Then yield responds positively with the addition of the nutrient, with a rate that progressively decreases up to a maximum point (Engels et al., 2011), while another nutrient becomes limiting. After that point, no respond to the same inputs is noticed, until the limiting factor is addressed. Consequently, the imbalanced addition of nutrients might not efficiently increase yields (Janssen, 1998) and might even lead to pollution, as a result of leaching of mobile nutrients, like N.

Determining required inputs

In order to achieve balanced and sufficient nutrition of the crop, that will ensure the vegetative growth of the tree and the production of high quality beans, a fertilization plan should be mapped out. This includes input types, their amounts and an application pattern in time and space. This study will focus on the amounts of nutrient sources required for coffee production.

In general, the approach used to determine required nutrient inputs includes matching soil supply and crop demand (Rose and Bowden, 2013). General guidelines can be used, but due to large variation in soil fertility that can exist even within the same farm (Tittonell et al., 2006), they need to be adjusted according to the local soil conditions and particularly the existing nutrient soil stocks, age of trees and the crop requirements depending on growth in relation to the weather (Vanlauwe and Giller, 2006).

The challenge lies not only in the determination of optimal application rates, but also the proportions of applied nutrients, to prevent imbalanced situations and inefficiency. The use of inorganic fertilizers to meet inputs demands can be easy, as they contain specific amounts of nutrients. However, when organic materials are used as inputs, the varying nutrient composition should be considered. This does not always match the crop needs, thus combinations of materials might be used. For example, grass mulch can be a good source of K, but too much can induce Mg deficiency (Carr, 1993). Also, the nutrient release patterns from the decomposing material should follow the crop growth demand.

A useful tool for the assessment of nutrient requirements of the coffee crop is the SAFERNAC model (Maro et al., 2014a). Its name stands for *Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee*. It is an empirical model, that combines soil chemical fertility, crop physiology and nutrient inputs to estimate expected coffee yields. It can function as a land evaluation tool to assess coffee yields when no nutrient inputs are provided. Alternatively, it calculates nutritional requirements in order to achieve target yields and can therefore be used to design a fertilization plan. SAFERNAC was developed by adapting and calibrating the QUEFTS model (Janssen et al., 1990) to coffee in Tanzania Coffee Research Institute's farm.

Empirical models are often site-specific (Sattari et al., 2014), as they only capture the limited variability of the development conditions. However, for a model to be a useful tool, it should carry the ability to generalize, i.e. the ability to be applied in a range of conditions (Dourado-Neto et al., 1998). So far, SAFERNAC has not been used to estimate yields or fertilization requirements or validated in environments other than the region in Tanzania.

Objective, research questions and hypotheses

The objective of this study is to explore nutrient management options for maintaining and achieving sufficient coffee yields with the use of the model SAFERNAC. To address this objective, the model will be first evaluated and if necessary calibrated.

In particular, the following research questions will be answered:

1. What is the accuracy of the SAFERNAC model in estimating coffee yields in Rwanda?
2. What adaptations in the model parameters are required in order to improve its accuracy?
3. What are common soil fertility management practices applied by farmers?
4. What is the effect of *Tephrosia vogelii* Hook. f. (hereon referred to as Tephrosia) intercropping with coffee on yields in comparison to common practices?
5. What are blanket nutrient management recommendations for coffee fields in Rwanda and how can the model be used to compare them?
6. What are required amounts and proportions of nutrients in order to achieve target yields?

The following hypotheses are formulated on basis of the research questions:

1, 2. It is expected that the model performance is satisfactory, but some of its parameters need to be fine-tuned by calibration to the local growing conditions.

3. The expectation is that farmers use mainly organic, but insufficient amounts of inputs.

4. It is hypothesized that intercropping coffee with Tephrosia improves coffee yields.

5. Blanket recommendations are expected to vary in terms of efficiency and effectiveness between farms.

6. Required amounts for nutrient inputs are expected to differ among farms, according to their existing nutrient soil stocks.

Materials and Methods

The study region

The study region is located at the Rubavu and Rutsiro districts of the Western province of Rwanda, at the north of the agricultural zone of Lake Kivu Borders (Fig. 1.1.). The main coffee species cultivated in this area under rainfed, unshaded conditions is *Coffea arabica*.

The climate is sub-equatorial, characterized by mean annual temperatures between 19^{o}C – 22.5^{o}C and average annual rainfall of about 1150 – 1300 mm (Verdoodt and Ranst, 2003). Seasonality is expressed in terms of rainfall rather than temperature, with two dry seasons, in June - September and in January – March. Despite this climatic bimodality, there is only one harvest season in Rwanda, which starts in March and ends in May.

In this region, 28 farms are participating in the project that this study is connected to. For the goals of that project, in each participating farm, a plot of 75 m^2 in a selected coffee field has been intercropped with the legume shrub Tephrosia. Every six months (Tephrosia growing season), the shrub is harvested and all its biomass is left fresh on the plot as mulch, while the acquired yields are monitored. The coffee fields are from now on referred to as "regular fields" (RF) and the embedded intercropped plots as "Tephrosia plots" (TP). Because on two farms, two TP in separate coffee fields were established, there are 30 RF and 30 TP.

The fields were chosen to include variation in terms of the reference soil groups (RSG) (IUSS Working Group WRB, 2014) that they belong to and their landscape position. Thus, they are divided in five RSG in an unbalanced design: Humic Acrisols (n = 11), Humic Ferralsols (n = 12), Dystric Leptosols (n = 3), Humic Alisols (n = 3), Technosols (n = 1). The soil texture of Dystric Leptosols and the Technosol is sandy loam, while the soils in all other groups are categorized as sandy clay loam. The altitude of the fields ranges from 1495 m to 1858 m above sea level.

Ferralsols, Acrisols and Alisols (IUSS Working Group WRB, 2014), which represent 26 out of 30 studied fields, are by definition highly acidic, originate from weathered parent materials and are characterised by low base saturation with a tendency for Al toxicity. More specifically, Ferralsols are acidic, contain many Fe^{3+} and Al^{3+} and a lot of clay minerals (kaolinite and oxides) that reduce the capacity to retain cations. They are strong weathered and they lack nutrients. Especially P is often fixed, thus unavailable for the plants. Alisols and Acrisols also contain many clay particles in the subsoil and plenty of Al^{3+}. They have a low base status and are also acidic. The difference between Alisols and Acrisols is that the former contain high activity clays, which make the ability to retain bases stronger than Acrisols, which contain low-activity clays. Dystric Leptosols are very thin soils with coarse particles, that pose limitations to root growth and they have a low effective base saturation status (IUSS Working Group WRB, 2014).

Data description and collection methods

Soil chemical fertility data

Composite soil samples of approximately 500 g each from the topsoil (0 - 20cm) were collected following a zigzag, systematic grid sampling protocol on the TP prior to the initiation of this experiment, in autumn 2015 and one year later, in October 2016, after two Tephrosia growing seasons. They were analysed in NAEB's (National Agricultural Export Development Board) laboratory in Rwanda, for pH(H_2O), Soil Organic Carbon (SOC) (g/kg), Total Nitrogen (TN) (g/kg), Phosphorus with Bray I test (P-Bray-I) (mg/kg), Exchangeable Potassium (K-exch) (mmol/kg) and soil texture. The analysis one year later excluded soil texture, but included P-Olsen (mg/kg). pH was determined in distilled water (1:2.5 soil to water) with a potentiometric method. SOC was assessed with oxidation in sulphuric acid (98%) and aqueous potassium dichromate (1 N) mixture ant 155^{o}C for 30 min and the remaining was titrated against ferrous ammonium sulphate (0.2 M). TN was determined with wet oxidation according to Kjeldhal in sulphuric acid (concentrated 98%) and hydrogen peroxide (30% w/v). Available P was extracted in hydrochloric acid (1 N) and ammonium fluoride (1N) for P-Bray-I and in sodium bicarbonate (0.5M) at pH 8.5 for P-Olsen, followed by colorimetry at 880nm in a mixture of ascorbic acid and Murphey Riley solution. Finally, K was determined with atomic absorption spectrophotometry in ammonium acetate (1M).

Even though SAFERNAC was developed with P quantified with Bray-I, QUEFTS uses P-Olsen. Therefore the Olsen method of P quantification in the soil was included in the soil analysis in order to identify if it is a better indicator of plant available P. If that would be shown, the model would be modified to include it in the calculations. Interestingly, despite this difference, the model assumptions were not adjusted by Maro et al. (2014a) to fit the P value ranges measured on their soils.

Various extraction methods of plant available P exist (Pierzynski, 2000). They differ based on the amount of P they can extract from the sample and on whether this amount agrees with the plant uptake. Often the result is dependent on the soil pH, as each extractant interacts with different forms of P in the soil (Schick et al., 2013). Wolf and Baker (1985) found higher P-Bray values than P-Olsen. Mallarino (1995) on the other side reported a relationship of Olsen = 3.5 + 0.42 * Bray-I, with R^2 of 0.77 in soils with pH < 7 and claimed that Bray-I was more accurate in acidic than in calcareous soils. Chilimbo et al. (2013) found a similar result, with Olsen = 0.5 * Bray-I - 0.1 (R^2 =0.7) and higher results of Bray-I in acidic soils. However, they found weak correlation of P extracted by all methods with the plant uptake by maize, even though Olsen proved to be the best. On the contrary, even though Azeez et al. (2013) also report that Bray-I extracted more P than Olsen, they measured better correlation of Bray-I with plant uptake than Olsen. In general, P-Bray-I is preferred in acidic (pH < 6.0) soils (Elrashidi, 2010).

The correlation between P-Olsen and P-Bray-I results in this study was explored with a Spearman's rank analysis. P-Bray-I managed to extract more P than the Olsen method in all the samples. Olsen and P-Bray-I were connected with a factor of 0.55 (R^2 =0.8, r_s = 0.88, p < 0.01) in acidic soils, which largely agrees with the aforementioned literature (Fig. 2.1).. This was one of the reasons that the modelling analysis was continued with P-Bray-I as SOIL variable. Also, Bray-I was chosen in order to maintain consistency with Maro et al. (2014a), but also because due to the strong correlation of the two methods, they can be interchangeably used as long as the model parameters are adjusted.

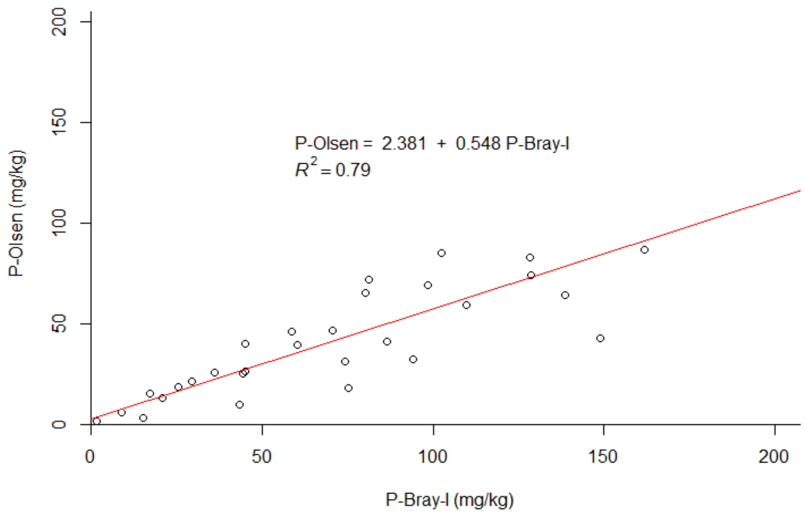


Figure 2.1. The correlation between Olsen and Bray-I testing methods for P quantification in the soil according to the soil analysis of samples collected one year after the establishment of Tephrosia.

Because error is always possible in any laboratory analysis (Motsara and Roy, 2008), one of the samples of the first analysis was delivered together with the second batch as blind, in order to check the reliability of the results. The values of the control sample deviated from the expected (original) ones (Table 2.1), therefore the analysis was rejected. According to NAEB's laboratory, the first analysis was performed by an inexperienced technician. The skills of the technician are major determinants of the error in the results (Ng et al., 1974). Consequently, the analysis was repeated by four different technicians. The differences between them were compared with a one-way repeated measures ANOVA and only the results for pH and P-Bray-I were found to significantly differ (results in Appendix 2.2a-b). It was decided to use the average value for all variables in the remaining of the analysis. This result agreed more with the first analysis in terms of all variables, except K. That deviated largely from both preceded analyses.

Table 2.1. The results for the blind sample: first analysis, rejected second analysis and accepted second analysis as averaged by the four technicians.

Analysis	**pH(H_2O)**	**SOC (g kg^{-1})**	**TN (g kg^{-1})**	**P-Bray-I (mg kg^{-1})**	**K-exch (mmol kg^{-1})**
First	5.2	13.1	2.75	56.88	1.2
Rejected	5.9	26.5	3.40	36.28	1.4
Accepted	5.5	12.9	2.63	54.80	0.4

Yield data

1. Coffee yields (kg parchment per tree per year) of the RF from 4 past seasons (years 2012-2015).

The green berry (= fresh matter) coffee yield per RF per year were acquired from the records of the local coffee washing station, who also recorded and provided the number of trees per field. Thus, the green berry yield per tree per year was calculated. The parchment (= dry matter) coffee yields per tree were calculated by multiplying the green berry yields per tree and a conversion factor (0.5598). This has been estimated by collecting a 500 g sample of green berries, which was weighted and then pulped, dried and weighted again.

2. Coffee yields (kg parchment per tree per year) of TP for 2016.

Green berry yields per tree per year from the TP were collected as part of the experiment. Parchment yields were calculated on basis of the green berry yields and a different conversion factor (0.25) than the one used for the yields acquired from the washing station, but estimated with the same methodology with a 500 g sample. The reason for the different conversion factors lies on the condition of the green berries at the moment of the first weighing. Those collected at the washing station had been harvested a few days earlier, which resulted in some water loss, while the ones from the Tephrosia trees were fresh. The conversion factor of 0.25 that connects green berries and parchment coffee can be traced in the literature (van der Vossen, 2005) and was confirmed by the representative of the local coffee washing station (Erik, personal communication). However, some other authors use the value of 0.2 (Janssen, 2004).

3. Coffee yields (kg parchment per tree per year) of RF for 2016.

Green berry yields from 8 trees in each RF were collected and converted to parchment yields using the 0.25 conversion factor. These trees were selected to have similar canopy structure and shoot number as the trees in the TP. The average yield across all years (2012-2016) was used for the analysis.

4. *Potential yield (kg parchment per tree, kg parchment per ha)* (Y_{max}).

The maximum parchment yield observed in the 30 fields in the years 2012-2016 was 2.24 kg parchment per tree, which equals to 4.48 tons per ha at 2000 trees per ha. This number was confirmed by the manager of the local coffee washing station in Rwanda, who mentioned that a good tree with proper management yields 10 kg of green berries per year, which corresponds to 2 – 2.5 kg parchment per tree (4 - 5 tons per ha) (E. Niyonshuti, personal communication, 2016). Bucagu et al. (2013) reported 2.8 tons per ha in Southern Rwanda.

In the greater region of the African Lakes, higher yields have been measured. Wrigley (1988) mentions that the yield of the best performing cultivar in Kenya has reached 4.9 tons parchment per ha, but admits that the average is 2.2 tons per ha. Wang et al. (2015) observed yields in coffee farms in Uganda above 3.1 tons per ha, even though they have considered them as outliers. However, often the plant density is not specified making comparison of yields measured in kg per ha difficult. Observed yields in the study region were high in comparison to the findings in the literature. To avoid problems during the model evaluation, the potential yield was set to the highest value observed in the researched farms, 4.5 tons per ha or 2.25 kg parchment per tree. The development of SAFERNAC (Maro et al., 2014a) involved yields of 3.4 tons per ha in the plots used for the calibration.

Management and input data

1. Usual management of the coffee trees and the RF.

In order to identify the usual management practices applied on coffee fields, the farmers participating in the experiment were interviewed in October and November 2016. The main aim of these interviews was to collect data about the soil fertility management, in particular types and quantities of inputs applied by the farmers on the RF. Inputs are defined as crop residues, compost, manure and mineral fertilisers, regardless of the farmer's purpose of application (sometimes mulch is applied for maintaining moisture, weed prevention etc). Additionally, information about the management of the coffee trees, like whether pruning and weeding is performed, or the fate of prunings was recorded, in order to identify possible major limitations in the production. The questionnaire used can be found in Appendix 2.3.

For the four fields that in pairs are owned by the same farmer, the same management per pair was considered. As one farmer was unavailable, he was not interviewed and his field was excluded from the analysis. Consequently, the RF dataset consists of 29 records. It was assumed that the management is similar across the years, as it was not possible to collect information about differences in time.

2. *Management of the TP.*

The participating farmers were instructed to manage the TP in the same way as the corresponding RF and like in previous seasons, with only exception the use of inputs and mulching. Regular plots received the usual farmers' inputs and mulch. Tephrosia plots received 100 g per tree of urea fertilizer (46% N) in granular form, applied close to the tree base, once in November and the fresh Tephrosia biomass twice (spring and autumn) as mulch, along with other, possible effects of the intercropping.

3. *Tephrosia dry biomass (kg) applied per plot at the end of the first Tephrosia growing season, in spring 2016.*

Six months after the planting of Tephrosia, in spring 2016, the shrub was harvested, weighted and applied on the field as mulch. A sample of each plot was taken and dried in order to determine the dry matter content. Then, dry biomass (kg) applied per plot (75 m^2) and per ha was calculated.

Conversion of input quantities to N, P, K amounts.

The model variables for the INPUT module are measured in kg N, P and K per ha, therefore the quantities of inputs (kg per ha) applied on both RF and TP were translated into amounts of nutrients (kg per ha) using secondary data of nutrient contents (mass fractions) for each material. Due to the large variability of such values that can be found in the literature depending on the region, growth stage, collection timing and other factors, in an effort to acquire comparable data for the various inputs, literature that contained nutrient contents of multiple materials was preferred. After a collection of possible values (details in the Appendices 2.4 – 2.5), they were logically assessed and filtered. For example, legume residues were expected to contain more N than non-legumes. The final values can be found in Table 2.2.

Table 2.2. Nutrient contents (% dry matter) of the materials applied by the farmers. When no source is reported for plant sources, the values were chosen in comparison to similar materials. ORD = Organic Resource Database (Palm et al., 2001)*, available at PPS: office.pp@wur.nl.*

Material	**N (%)**	**P (%)**	**K (%)**	**Source**
Napier grass leaf (*Pennisetum sp.*)	1.97	0.14	3.85	ORD
Maize stover (*Zea mais*)	0.43	0.14	1.23	(Smaling et al., 1993)
Banana leaf (*Musa sp.*)	2.5	0.13	2.66	ORD
Banana trunk (*Musa sp.*)	0.73	0.18	4.1	ORD
Banana peels (*Musa sp.*)	1.16	0.64	4.63	(Lekasi et al., 1999)
Soybean straw (*Glycine max*)	0.6	0.1	0.9	(Nijhof, 1987)
Soybean leaf (*Glycine max*)	3.47	0.18	1.57	ORD
Bean leaf (*Phaseolus sp.*)	3.72	0.26	2.75	(Sanginga and Woomer, 2009)
Bean stover (*Phaseolus sp.*)	0.99	0.11	1.93	(Sanginga and Woomer, 2009)
Themeda sp. whole plant	0.55	0.056	0.48	(Paliwal and Manoharan, 1987)
Sugarcane leaf (*S.officinarum*)	1.21	0.14	1.16	(Bokhtiar et al., 2008)
Tephrosia vogelii whole plant	3.01	0.18	0.9	(Bucagu et al., 2013)
Cattle Manure	1.3	0.6	1.4	(van der Vossen, 2005)
Goat Manure	2.8	0.6	2.4	(Harris, 2002)
Sheep Manure	2	0.2	1.7	(Henao and Baanante, 1999)
Poultry Manure	1.03	0.22	1.93	(Harris, 2002)
Pig Manure	0.6	0.14	0.29	(Henao and Baanante, 1999)
Rabbit Manure	1.6	0.4	0.5	(Sanginga and Woomer, 2009)
Coffee Pulp	2.8	0.56	4.24	(van der Vossen, 2005)
Weeds Other Fields	1.2	0.12	1.1	-
Compost	2.6	1.49	2.13	ORD
Leftover animal feed	0.4	0.05	0.5	-
Urea	46	0	0	-

Only materials grown outside the fields were considered, therefore weeds from the coffee field or crop residues from possible intercropping were excluded from the calculation. For the same reason, in the case of the TP, only the amount of N fixed by the shrub was considered. This amount can range from 58 – 73 % (Giller, 1993). In this assignment it was set to 65% of the N in the plant. However, nodulation was not checked, therefore it is not certain that fixation indeed took place. Other mechanisms of N transfer from the legume to the coffee were not considered. Nutrients imported in the system in other ways than organic mulches or mineral fertilisers, for example deposition, were not considered.

For the calculation of nutrient inputs from manures, it was assumed that manure of the animals owned by the farm was used, unless otherwise explicitly mentioned by the farmer. When one farm owned multiple types of animals, the contribution (kg) of each type was calculated based on the relative manure production per animal using the ratio Cow : Goat : Sheep : Chicken : Pig : Rabbit = 4:0.4:0.5:0.02:1:0.05 (RVO, 2017).
When farmers reported the use of a mixture of manure and compost, a ratio of 50:50 was assumed, since no better alternatives were available. When they also mixed leftover animal feed, this was assumed to be 20% and the remaining an equal mixture of manure and compost.

Dry matter of manures was set to 60% (Drechsel and Reck, 1997; Rufino et al., 2007), of composts to 40% (Drechsel and Reck, 1997) and of coffee pulp to 20% (Orozco et al., 1996).

The way of manure storage can affect significantly its composition (Harris, 2002; Tittonell et al., 2010) and can lead to losses up to 60% for N and up to 10% for P (Mafongoya et al., 2006). Uncovered heaps can lose 50% of their N within 7 months, while in covered conditions these loses are limited to 20% (Rufino et al., 2007). However, Fowler et al. (Fowler et al., 1993) recorded no large nutrient losses from the storage of manure. The manure management among the interviewed farmers varied, from direct application to the field to yearly collection and application. To maintain simplicity in this report, such losses of nutrients were not accounted for.

Usually crop residues are collected during the dry season, left to dry and then applied on the field. Thus it was assumed that most of the moisture of crop residues is removed by the time of application. Additionally, this implies that decomposition does not start until the rainy season has begun. Therefore, the effect of the storage period and method on the nutrient content of the these materials was considered insignificant.

The application method was always mulching without incorporation. Farmers make an effort not to disturb the soil as they try to prevent root damage of the coffee trees. Even though mulching can offer various benefits, like moisture retention or prevention of weeds, the failure to incorporate organic inputs in the soil can result in loss of nutrients.

The decomposition rate and pattern in time was also not considered, as the relative effectiveness of organic sources is included as a parameter in the SAFERNAC model (Maro et al., 2014a). It was thus deemed beyond the scope of this thesis to elaborate on this topic. It was assumed that if decomposition is not complete within one season, this happens the seasons after. Since this is a multi-year analysis, the residual effects are assumed to be not relevant.

Finally, none of the farmers was able to give precise information on the type of fertilizer used in the regular fields. Often the answer was simply “NPK”. To maintain simplicity, urea was considered to be the form of fertilizer added in the regular plots too, as in the Tephrosia plots. The model was run with other options too, but because the amounts of fertilizer used were not high, the effect on the results was also not large and they were not shown.

Since the size of the farm in ha was not known and was difficult to be estimated by the farmer during the interview, the number of trees reported by the farmers used to calculate the amount of mulch (or kg nutrient) per tree, which was then extrapolated to the ha using the recorded plant density.

Crop parameters

1. *Plant density (NrTrees).*

This was set at 2000 trees per ha (row distance * tree distance = 2.5 m * 2 m).

2. *Number of trees per farm.*

The number of trees per farm was asked to the farmers. This information was used to convert the amounts in kg of inputs on the RF, which was reported by the farmers over the whole farm, to kg per ha.

3. Physiological efficiency (PhE) (kg parchment/kg total crop uptake).

As no measured data on nutrient uptakes and harvest index were available, the default values of PhE, as reported in Maro et al, 2014, were used, as seen in Table 2.3.

Table 2.3. Default values of PhE per nutrient at dilution (PhE_D) and accumulation (PhE_A) (Maro et al., 2014a).

	N	P	K
Dilution	21	120	24
Accumulation	7	40	8

Data analysis and modelling

Software

All analyses were performed using R version 3.4.0 (R Core Team, 2017) in RStudio 1.0.143. The model was initially developed in Excel, but for efficiency and transparency, an existing R script for QUEFTS was adjusted and all modelling exercises were also continued in RStudio. The R code with the model is presented in Appendix 2.6.

Exploratory data analysis

Descriptive statistics (mean, median, standard deviation, standard error, interquartile ranges) were calculated for the soil and input variables and the yield data. Normal distribution was checked whenever necessary with QQ-plots and Shapiro-Wilk tests. Outliers were identified but not excluded from the analysis, to prevent losing statistical power due to a small sample. Soil variables were checked with scatterplots to reveal any collinearity. The ratio of the three nutrients (N, P, K) added in each RF was calculated to identify which is the most limiting nutrient and the nutrient in excess.

The relationships of across-years average RF yield and TP yield of 2016 with the soil variables were checked with multiple linear regression. The model included the yield as dependent variable and pH, SOC, TN, P-Bray-I and K-exch as independent variables. Furthermore, a multiple linear regression of observed RF yields as dependent variable and the amounts of N (organic and inorganic), organic P and organic K as the predictors was fitted to identify if input use is effective, as farmers use different amounts of mulches and fertilizer according to their access to resources. Finally, a linear model with TP yields as dependent variable and the total amount of N (organic and inorganic) applied as predictor was fitted to identify if these inputs explain yields.

The SAFERNAC model

SAFERNAC is a model that uses data on soil chemical fertility and applied nutrient inputs, which combines with information on the crop physiology in order to calculate the expected coffee yields on the specific farming system.

The explanatory variables required by SAFERNAC are grouped in three modules: the SOIL, the nutrient INPUT and the CROP module.

The variables of the SOIL module refer to the chemical fertility of the 0 - 20 cm topsoil and they are a measure of its indigenous supply, i.e. the available nutrients in the soil itself. They include the pH measured in water (pH(H_2O)), the soil organic carbon (SOC) (g/kg), the plant available P, measured with the Bray I method (P-Bray-I) (mg/kg), the total nitrogen (TN) (g/kg) and the exchangeable cation K (K-exch) (mmol/kg).

The INPUT module is comprised of three variables that refer to the amounts (kg/ha) of Nitrogen (N), Phosphorus (P) and Potassium (K) applied from organic sources (ON, OP, OK) and inorganic fertilizers (INN, INP, INK). These variables can be manipulated to improve the indigenous soil fertility or correct nutrient imbalances.

Finally, the variables of the CROP module are the plant density (NrTrees) (trees/ha), the potential yield (kg/ha) (Y_{max}) and the maximum and minimum values of the physiological or utilisation efficiency (PhE_D, PhE_A respectively) of the crop (kg/kg) for each of the three nutrients (Eq. 1). This module allows for adjustments based on the crop cultivar and the characteristics of the cropping system.

$$PhE = \frac{Yield}{Nutrient\ Uptake} \qquad \text{(Janssen, 2011a)} \qquad (1)$$

Where, *Yield* (kg) is the dry matter production of the economically interesting product, which in the case of coffee is the parchment (i.e. the remaining of the de-pulped, dried coffee berry) and *Nutrient Uptake* (kg/kg) is the amount of a nutrient that is taken up the whole crop.

The model combines the explanatory variables in a four-step procedure to calculate as output variable the coffee yield (kg parchment/ha).

In *Step 1*, the potential supply of each nutrient (SN, SP, SK) (kg/ha), i.e. the maximum amount of the soil available nutrient that can be taken up by the plant if no other liming growth factors exist (Janssen et al., 1990), is calculated as a function of the SOIL and INPUT variables and the tree density (Eq. s 2 – 4).

$$SN = (fN * betaN * SOC + recN * INN + recN * relefN * ON) * fD \quad (2a)$$

$$SN = (fN * alfaN * TN + recN * INN + recN * relefN * ON) * fD \quad (2b)$$

Equations 2a and 2b can be used interchangeably if the C:N ratio of the soils equals 10 (Janssen et al., 1990). In this study, the C:N ratio was 7.4 ,thus Equation 2a was used.

$$SP = (fP * alfaP * SOC + betaP * PBrayI + recP * INP + recP * relefP * OP) * fD \quad (3)$$

$$SK = \left(\frac{fK * alfaK * Kexch}{SOC} + recK * INK + recK * relefK * OK \right) * fD \quad (4)$$

Where:

fN, fP, fK	correction factors related to the soil pH (Eq. 5 - 7),
fD	correction factor related to the tree density (Eq. 8),
recN, recP, recK	recovery fractions or Uptake Efficiencies of each nutrient (kg/kg) (Eq. 9 for N, similar for P and K),
relefN, relefP, relefK	relative effectiveness of nutrients in organic sources, enclosing the process of decomposition and nutrient release,
betaN, alfaN, alfaP, betaP, alfaK	model parameters.

$$fN = slN * pH + icN \quad (5)$$

$$fP = icP + sl1P * pH + sl2P * pH^2 \quad (6)$$

$$fK = slK * pH + icK \quad (7)$$

Where slN, icN, icP, sl1P, sl2P, slK, icK are model parameters.

$$fD = 0.5 * \frac{NrTrees}{1000} - 0.06 * \left(\frac{NrTrees}{1000}\right)^2 \quad (8)$$

The fD factor (Eq. 8) takes values from 0 – 1, with 1 at optimal tree density of 4333 trees/ha and it represents the effect of tree density on the nutrient potential supply, thus the modelled yield. In the same soil conditions and nutrient management, increasing the number of trees will increase yields, until the resources are fully exploited, thus competition will occur. Tree density affects among others the utilization of the soil nutrients and the competition at the root zone, but also the extent of ground cover and the shading. High densities increase shading, which in turn affects floral initiation, therefore, the amount of fruits the tree will carry (Wrigley, 1988). Additionally, light interception on the field level is smaller at low densities, hence yields per ha are lower (Wrigley, 1988). According to Wringley, (1988) at tree densities of 2000 trees per ha, ground cover can range from 40 - 80%.

$$recN = \frac{Nutrient\ Uptake}{Nutrient\ available} \quad \text{(Janssen, 2011a)} \quad (9)$$

Where *Nutrient available* is the amount of available nutrient for uptake.

In *Step 2*, the actual uptake (UN, UP, UK) of each nutrient is determined, according to its relative potential supply to the others. In particular, for each pair and a given availability of the third three situations can be identified; the potential supply of one is small in comparison to the other, intermediate or very large. In the first case, the nutrient is limiting, thus all available quantity will be taken up (Eq. 10). It is then considered to be fully diluted in the crop. In the second, it is in excess, hence, some will be taken up and the rest will remain in the soil (Eq. 11). The nutrient is accumulated. In the last situation, the uptake increases with a rate that progressively decreases (Eq. 12). Eventually, all three actual uptakes are calculated.

If it holds that $$SN < SP * \frac{PhE_{A,P}}{PhE_{D,N}} \quad \text{then} \quad UN = SN \tag{10}$$

if $$SN > SP * \left(2 * \frac{PhE_{D,P}}{PhE_{A,N}} - \frac{PhE_{A,P}}{PhE_{D,N}}\right) \quad \text{then} \quad UN = SP * \frac{PhE_{D,P}}{PhE_{A,N}} \tag{11}$$

else $$UN = SN - 0.25 * (\frac{\left(SN - SP * \frac{PhE_{A,P}}{PhE_{max,N}}\right)^2}{SP * \left(\frac{PhE_{D,P}}{PhE_{A,N}} - \frac{PhE_{A,P}}{PhE_{D,N}}\right)} \tag{12}$$

In *Step 3* a range of minimum maximum yields per nutrient is determined (YN_A, YN_D, YP_A, YP_D, YK_A, YK_D) according to whether the nutrient is in dilution or in accumulation respectively (Eq. 13 – 14 for N and similar for P and K).

$$YN_A = UN * PhE_A \tag{13}$$

$$YN_D = UN * PhE_D \tag{14}$$

Finally, in *Step 4* the overlapping yield range per pair of nutrients is identified and two combined yields (YNP, YPN and YNK, YKN and YKP, YPK) are calculated for each pair with Equation 15 (for N and P). The final yield is the average of the 6 combinations. The potential yield (Y_{max}) is taken into consideration as none of the combined yields can exceed it.

$$YNP = YPA + \frac{2 * (YND - YPA) * \left(UN - \frac{YPA}{PhE_{D,N}}\right)}{\left(\frac{YND}{PhE_{A,N}} - \frac{YPA}{PhE_{D,N}}\right)} - \frac{(YND - YPA) * \left(UN - \frac{YPA}{PhE_{D,N}}\right)^2}{\left(\frac{YND}{PhE_{A,N}} - \frac{YPA}{PhE_{D,N}}\right)^2} \tag{15}$$

The default values of the model parameters can be found in Appendix 2.7.

According to Maro et al. (2014a), the model assumes that other growth factors are at optimal levels and only the three nutrients are limiting yield. Further, it requires that the soil depth is bigger than 90 cm, the soil drainage class is at least 3 and for the topsoil (0 - 20cm) it holds that pH(H_2O) is between 4.5 - 7.0, SOC is lower than 70 g/kg, P-Bray-I is less than 30 mg/kg and K-exch is less than 30 mmol/kg. However, the soil characteristics that they used for the calibration were not always compliant with these assumptions, as P-Bray-I values ranged from 65 – 119 mg/kg.

Model evaluation and calibration

Sensitivity analysis

A sensitivity analysis of the model to the SOIL (pH, SOC, P-Bray-I, exch. K) and INPUT (organic and mineral N, P, K added) variables and the physiological efficiencies was performed as first step in order to gain a better insight in the model functioning. Such approach also helps to get a deeper understanding on the required measurement accuracy of the model variables and the effect of measurement inaccuracies on the response variable (final or modelled yield) and to estimate the extend of the expected differences in the response variable among different farms.

The modelled yield is expected to increase until at least one of the nutrients becomes limiting. At that point, even if the other nutrient(s) are in sufficient supply, the increase rate of the yield will decelerate and eventually stop. When no inputs are added in the model, the final yield depends on the soil indigenous supply. With the addition of inputs, this availability can be manipulated. Hence, the starting values of variables and parameters are affecting the model response and for this reason various scenarios were examined.

The exploration of the effect of the SOIL variables on the yield was done considering seven soil chemical fertility scenarios with different indigenous supply (Table 2.4) without addition of inputs. "Tanzania" is based on the average conditions where the model was calibrated. "Rwanda" is based on the average conditions of the farms of this study. The soils "Poor", "Average", "Rich" are supposed to represent relatively proportional supplies of the nutrients at three different levels (so that none of them becomes limiting very soon before the others in the analysis).

Table 2.4. Seven soil fertility scenarios used for running the sensitivity analysis.

Soil	**pH**	**SOC (g/kg)**	**TN (g/kg)**	**P-Bray-I (mg/kg)**	**K-exch (mmol/kg)**
Poor	5.1	10	0.1	10	1.0
Average	5.5	15	1.5	30	3.0
Average + extra P	5.5	15	1.5	60	3.0
Average + extra K	5.5	15	1.5	30	6.0
Rich	6.0	30	3.0	90	15.0
Tanzania	5.6	20	2.0	90	20.0
Rwanda	5.5	15	3.0	70	1.5

From the initial condition, the value of each variable was varied within feasible, but slightly exaggerated ranges according to the values that have been recorded in the soil analysis (Table 2.5). The SOIL variable TN was not included as Equation 2a and not 2b was used in the model calculations, thus the model does not respond to it. The predicted yield in each run was recorded and plotted against the explanatory variable.

Table 2.5. Value ranges of soil variables used in the sensitivity exercise.

	pH	**SOC (g/kg)**	**P-Bray-I (mg/kg)**	**ExchK (mmol/kg)**
Minimum value	3.5	0.1	0.1	0.1
Maximum value	8.0	40.0	120.0	20.0

The sensitivity of the model to nutrient inputs was tested with a sensitivity analysis for the INPUT variables. On basis of an average soil (Table 2.4) two levels of each nutrient were added (150 or 300 kg/ha) one by one, followed by the addition of two nutrients, in every combination and eventually, the addition of all three nutrients according to Table 2.6. Inputs of inorganic P and K were not considered, as they are not applied in the RF or the TP.

Table 2.6. Fertilization plans for running the sensitivity analysis to the INPUT variables. ON, OP, OK = organic N, P, K. INN, INP, INK = Inorganic N, P, K.

Scenario	**INN (kg/ha)**	**INP (kg/ha)**	**INK (kg/ha)**	**ON (kg/ha)**	**OP (kg/ha)**	**OK (kg/ha)**
None	0	0	0	0	0	0
ON	0	0	0	150/300	0	0
INN	150/300	0	0	0	0	0
INP	0	150/300	0	0	0	0
INK	0	0	150/300	0	0	0
INN-INP	150/300	150/300	0	0	0	0
INN-INK	150/300	0	150/300	0	0	0
INP-INK	0	150/300	150/300	0	0	0
INN-INP-INK	150/300	150/300	150/300	0	0	0

Finally, the model's response to doubling or halving the values of the physiological efficiencies was studied with a simulation of an "average" and a "Rwandan" soil (Table 2.4).

Elasticity analysis

An elasticity analysis was performed as well, in order to quantify the sensitivity of the model to its parameters. Elasticity (E) is an index that quantitatively expresses the sensitivity of the model to relatively small changes in parameter values. It is calculated according to the Equation 16.

$$E_{s,p} = \left(\frac{(S_{p=max} - S_{p=min})}{(P_{max} - P_{min})}\right) \cdot \left(\frac{P_{default}}{S_{p=default}}\right) \qquad \text{(Schut, n.d.)} \qquad (16)$$

Where P is the parameter value and S_p is the outcome variable at a particular P.

Elasticity was calculated for all the recovery fractions, the relative effectiveness of the organic sources, and the parameters betaN, alfaN, alfaP, betaP, alfaK. The default values were varied by ±10% one at a time. As with the sensitivity analysis, the model response changes according to the initial state of the system and is stronger to parameters related to the most limiting nutrient. To explore this model behaviour, elasticity was calculated with five system configurations: three without nutrient inputs and either the soils "Rwanda", "Tanzania" and "Average" (Table 2.4) and two on "Rwanda" soils and an average case of either Tephrosia inputs (38.8 kg/ha organic N and 92/ha kg inorganic N) or regular inputs (207 kg/ha organic N, 34.7 kg/ha organic P, 361 kg/ha organic K and 92 kg/ha inorganic N).

Model evaluation

A model can be evaluated in terms of its consistency with the existing scientific knowledge ("scientific evaluation") or its ability to predict accurately and precisely ("operational evaluation") (Willmott et al., 1985). Accuracy is the agreement of the predicted outcome with a set of independent, measured values and precision refers to the ability of the model to predict values that are linearly related to the observations (Willmott et al., 1985). This section will focus on the operational evaluation of the model SAFERNAC. The goal of the evaluation was to assess its predictive ability in conditions different than where it was calibrated.

Various model evaluation tools exist (Mayer and Butler, 1993; Wallach et al., 2014; Willmott et al., 1985). Each of them has both advantages and disadvantages, thus the best strategy is the choice of more than one of them (Mayer and Butler, 1993). The following approach is used here:

1. Graphical evaluation

   Observed yield data were plotted against the modelled corresponding values. On this graph the 1:1 line is indicated. Ideally, all data points fall on it. Model error is the vertical (or horizontal) distance of a point from this line (Mayer and Butler, 1993).

2. Quantitative evaluation

   The goodness-of-fit is quantified with the following measures:

   a. A linear model is fitted through the datapoints and the R^2 (Eq. 17) is calculated. The fitted line is plotted to give an indication of the deviation from the 1:1 line and the fitness of the model.
   b. The Mean Square Error (Eq. 18), which is measured in $(kg/ha)^2$. It can further be analysed into the systematic error (Eq. 19), i.e. to what extend the model consistently over or underpredicts (bias), and the unsystematic error (Eq. 20), i.e. the scatter or variability of the predicted values (Wallach et al., 2014).
   c. The root mean square error (RMSE). RMSE is calculated as the root of the mean square error (MSE) (Eq. 21). Its advantage is that it has the same units as the outcome variable (in this case kg/ha).

$$R^2 = \sum_{i=1}^{n} \left(\frac{(\bar{y} - \widehat{y_i})^2}{(y_i - \bar{y})^2}\right) \qquad \text{(Field et al., 2012)} \qquad (17)$$

Where y_i is the observed data, $\bar{y}$ is the mean of the observed data, $\widehat{y_i}$ are the predicted values by the model

$$MSE = \left(\frac{1}{n}\right) \sum_{i=1}^{n} (y - \hat{y})^2 \qquad \text{(Wallach et al., 2014)} \qquad (18)$$

$$MSE_{SYS} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \left(y - \widehat{y_{reg}}\right)^2 \qquad \text{(Wallach et al., 2014)} \qquad (19)$$

Where $\widehat{y_{reg}}$ are the predicted values based on the regression model of $\hat{y}$ on y

$$MSE_{UNSYS} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \left(\hat{y} - \widehat{y_{reg}}\right)^2 \qquad \text{(Wallach et al., 2014)} \qquad (20)$$

$$RMSE = \sqrt{MSE} \qquad \text{(Wallach et al., 2014)} \qquad (21)$$

The aforementioned evaluation tools were applied on the two datasets of RF (n = 29) and TP (n = 30) separately and a dataset that included both RF and TP (n = 59). Each dataset is comprised of the amounts and types of nutrient inputs applied on either the RF or the TP and of the respective acquired yields. The variables of soil chemical fertility measured from before the establishment of the experiment were used.

Error exploration

To get an insight in the model error and reveal possible patterns related to one or more of the explanatory variables, the residuals (observed minus predicted value) were plotted against the modelled yields and each of the SOIL and INPUT variables (Wallach et al., 2014).

Model calibration

The evaluation of the model resulted in unsatisfactory scores of the accuracy measures, thus it was decided to proceed with its calibration. Model calibration is the adjustment of its parameters in order to improve the goodness-of-fit. The need for parameter estimation is not uncommon in modeling (Wallach et al., 2014) and has often been done with QUEFTS after its development, when it was applied in different conditions or crops (Das et al., 2009; Nyombi et al., 2010; Sattari et al., 2014; Smaling and Janssen, 1993).

The detailed steps of the calibration are as follows:

First, the predictive accuracy of the model ($RMSEP_{val}$) was assessed.

a. Only the data from the Tephrosia plots were used, as during the model evaluation, they showed to be less scattered, even though largely biased. The data was split in two subsets; a training set, containing 70% of the data and an evaluation set with the remaining 30%. There are various ways to do this (Reitermanová, 2010). The simplest is random sampling of 70% of the data as training set and 30% for testing.
b. All parameters were calibrated using the training set. The value of each parameter was varied within feasible ranges (Appendix 2.7) that include a reasonable number of in-between steps. In each step, the accuracy measure $RMSEP_{cal}$ (Eq. 21) and the R^2 (Eq. 17) were calculated. The parameter value that gave the lowest $RMSEP_{cal}$ value was selected, according to the principle of Ordinary Least Squares. The procedure was continued with the next parameter.
c. The evaluation set was used with the improved parameters to calculate the $RMSEP_{val}$. This expresses the expected error when making model predictions and is based on Equation 21.

This process was repeated 100 times in what is called a bootstrap; i.e. repeating a calculation multiple times with a new splitting of the dataset each time. Eventually, a vector of $RMSEP_{val}$ values is produced, from which the mean value and confidence interval (CI) can be derived.

The importance of the bootstrapping lies in the data splitting. Even though done in a random manner, it might result in the placement of outliers or fields with particularities in the training or the testing set, and in this way create bias. Thus the acquired value of $RMSEP_{val}$ might not be accurate. When the splitting is repeated multiple times, the sampling distribution, thus the standard error of the mean $RMSEP_{val}$ can be calculated, which gives an indication of its accuracy.

Eventually, the new parameter values were estimated using all 30 datapoints of the TP. This is the same procedure as above, excluding the data splitting and the bootstrapping. This process resulted in the new parameter set, which formed the "improved model". Through this process, the $RMSE_{cal}$ can be calculated.

The parameter estimation was done on the model in one step, using the soil fertility data, the input information and the recorded yields. Soil chemical fertility status of before the experiment's establishment was used because it was more relevant for that season's yields (2016).

The first effort to calibrate the model included all model parameters without limitation in their allowed values. It appeared that it was possible to correct the initial bias of TP data to some extent, but the chosen values were greatly deviating from the originals. Since the values of those parameters are poorly understood, this approach was abandoned, to avoid creating unrealistic suggestions. The results are not reported.

The calibration order of the parameters matters, as when one of them is calibrated, the sensitivity of the model to the rest changes. Ideally, the parameters that trigger larger model response according to the elasticity should be adjusted first. This principle was adapted to the particularities of the data, as explained hereafter.

First, Tephrosia biomass was applied in March. The rainy season starts at that time of the year, and the decomposition and N release from mulch can be rapid (Jama and Nair, 1996). Nevertheless, the application has to synchronise well with the uptake requirements. Since trees have already set fruit at that time and given the K limitation in these soils, the uptake of N might have been lower than the available amount. Thus, the recovery fraction of N (recN) and the relative effectiveness of the organic N (relefN) were expected to be lower than the default (Bote, 2016).

According to the elasticity analysis, the most influential parameters depend on the soil fertility and inputs on the tested fields and eventually, on the most limiting nutrient. In the case of the TP, the elasticity revealed that the model was most sensitive to parameters related to K, as this was the most limiting nutrient. Thus the calibration continued with a focus on K.

In particular, since trees in the TP achieve yields of up to 2 - 2.5 kg parchment per tree under conditions of very low K availability, a possible explanation was speculated to be that the cultivar of the Rwandan farmers is one that is efficiently utilizing K. Thus, the PhE values of K were assumed to be higher than the original. To calculate them, first, the effect of a higher harvest index than the default was explored. In Maro et al. (2014a) a harvest index of 0.26 is derived from literature data, however, in Cannell (1985) harvest indexes (= ratio of dry biomass in coffee parchment to total above-ground dry biomass) of up to 0.5 are mentioned. Additionally, the minimum and maximum N, P, K mass fractions of a whole coffee tree were adjusted according to the values proposed in Nijhof (1987) (N: 0.55 – 2.30, P: 0.05 – 0.21, K: 0.45 – 2.50). Therefore, the PhE values were calibrated next, starting with that of K. The PhE of P followed, as it was also rather limiting and finally, the values for N were adjusted.

Finally, the parameters betaN, alfaN, alfaP, betaP, alfaK were calibrated, but because the processes they represent are poorly understood, the allowed deviation from the default values was limited. The coefficients of correction factors fN, fP, and fK (slN, icN, icP, sl1P, sl2P, slK, icK) were not recalibrated because they were considered to represent soil processes that do not differ much in different soils. Additionally, because P and K are not added in the TP the calibration of their recovery fractions was meaningless.

Final evaluation

The evaluation of a model requires an independent dataset, otherwise the fitness will be overestimated (Wallach et al., 2014). For this reason, the data of the RF were used to assess the improved model with the same process as in the initial model evaluation. This dataset was chosen despite its variability as it was the only independent one available. The soil chemical fertility variables of before the experiment's establishment were used.

Nutrient management with the SAFERNAC model

The goal of this section is to compare common fertilization options, with particular focus on the regular management and the Tephrosia intercropping, while exploring the model's ability to make recommendations for inputs in order to maintain the soil fertility in the coffee fields.

Despite the poor accuracy of the improved model, this analysis was continued. The results can therefore be considered as indicative and only major trends can be identified. The focus will be on further identifying strengths and weaknesses of the calibrated model.

Common nutrient management practices and tree maintenance

The most common nutrient sources used by farmers on the RF and the coffee tree maintenance practices were explored with simple descriptive statistics.

Assessment of Tephrosia intercropping

Aim of this analysis was to assess the effect of Tephrosia intercropping on the soil chemical fertility and on yields. First, the effect of Tephrosia on the soil was assessed on basis of the soil analysis. The effects of differences in soil data were assessed with paired t-tests for the variables that showed normal distribution (pH and TN) and Wilcoxon rank-sum tests for SOC, P-Bray-I and K-exch, that were not normally distributed even after transformation. The model was also run with the soil data before and after, without inputs. The modelled yields without inputs with the soil data before and after represent the land potential with the regular management and the intercropping respectively. They were compared with a Wilcoxon rank-sum test and a Spearman correlation.

Additionally, the difference between observed TP yields of 2016 and the average yield of RF for all years was checked with a paired t-test, after the variables were compared to the normal distribution. The observed yields were also explored per farm visually with a boxplot. The modelled RF and TP yields were compared with a paired t-test and a Pearson correlation.

Comparing common nutrient management practices

Various fertilization options were explored, in order to compare the predicted yields. (All application rates are expressed on per year basis.)

NI: Without the addition of any inputs

U: Urea 46% (100g per tree)

T: Tephrosia at an average recorded rate (40 kg ON /ha)

F2: NPK 17-17-17 (120 g per tree) + urea 46% (75 g per tree) (Nzeyimana et al., 2013)

F3: NPK 20-10-10 (400 g per tree) (IFDC, 2014; Nzeyimana et al., 2013)

RM: Average common practice, as recorded with the interviews (ON=228.7 kg/ha, OP=32.2 kg/ha, OK=405.8 kg/ha, urea 46% = 38.6 kg/ha)

P: Only *Pennisetum sp.* (6 kg dry matter per tree). This amount is large, however, it refers to the average farmers' practice as recorded with the interviews.

This approach simply compares common practices of Rwandan coffee farmers, or blanket recommendations (Ezui et al., 2016). Actually, the options are not comparable as different quantities of each material is used. A better approach is to calculate the effect of each material on yields per nutrient added. This was done using the method of Bucagu et al. (2013), where the Agronomic Efficiency (kg/kCNE) is calculated, according to Equation 22 (Vanlauwe and Zingore, 2010).

$$AE = \frac{Yield\ gain}{Nutrients\ added} \quad (22)$$

where $Yield\ gain$ (kg/ha) equals to the difference of the yield with no inputs and the yield acquired with nutrient inputs, and $Nutrients\ added$ (kCNE/ha) is the total amount of all three nutrients added, measured in crop nutrient equivalents (Janssen, 1998).

Crop nutrient equivalents (kCNE) are units of the quantities of P and K that affect yields in the same way as 1 kg N (Janssen, 1998). The ratio medium physiological efficiency of N (PhENm) to medium physiological efficiency of P (or K) (PhEPm or PhEKm) can be used as conversion factors of nutrient quantities in kg to kCNE. (Janssen, 2011b), where PhEm is the average value of PhE_A and PhE_D. Given the calibrated values of efficiencies (Table 3.10) for coffee used in this report, it holds that 1 kCNE N equals 0.65 kCNE P and 0.86 kCNE K (this ratio before the calibration was 1:0.175:0.875 (Maro et al., 2014a)).

Fertilization recommendations for target yields

The previous analysis gives indications on expected yields when the specific nutrients are added. However, not all options give satisfactory yields for all fields as they differ in their indigenous soil fertility. Additionally, criticising common methods of fertilization planning would not be constructive without offering an alternative. The model was used to identify required quantities of nutrients to achieve a target yield of 4000 kg/ha. Because each farm has different soil indigenous supply, it was inefficient to calculate exact amounts. This possibility exists, however, in SAFERNAC. As alternative, a factorial fertilizer trial was simulated, with 14 treatments (control, only one nutrient at a time, at sufficient rates, and two nutrients at sufficient amounts and the third in progressively increasing amounts).

The rates applied were for N and K: 100 kg/ha, 200 kg/ha, 300 kg/ha and for P: 150 kg/ha, 300 kg/ha, 450 kg/ha. The reason for the higher P application rates is its very low recovery fraction (0.1 kg/kg). In each treatment, the number of farms achieving at least the target yield was recorded and the most effective combination for each one was chosen.

Results

Exploratory data analysis

Soil variables

Descriptive statistics for the soil variables used in this report are given in Table 3.1. Soils were in general high in P, but low in K. The pH(H_2O) indicated slightly to moderately acidic soils. The values of pH(H_2O), SOC, TN and K-exch fell within the model boundary conditions, while P-Bray-I exceeded them for 76% of the farms. The calculated soil C:N ratio was on average 7.4. The scatterplots for each pair of soil variables did not show strong correlations between them (Appendix 3.1).

Table 3.1. Descriptive statistics for the soil variables before (B) and after (A) the establishment of the experiment. n = 30, SD = standard deviation, SE = standard error.

Variable	Units	Mean	Median	SD	SE	1st Quantile	3rd Quantile
pH(H_2O) (B)	-	5.50[a]	5.51	0.28	0.05	5.30	5.69
pH(H_2O) (A)	-	5.61[b]	5.62	0.31	0.06	5.36	5.89
SOC (B)	g/kg	15.84[a]	16.25	7.02	1.28	11.57	20.28
SOC (A)	g/kg	19.91[b]	20.60	7.25	1.32	18.27	22.15
TN (B)	g/kg	2.73[a]	2.70	1.24	0.23	2.00	3.11
TN (A)	g/kg	2.86[a]	2.90	1.23	0.22	2.30	3.20
P-Bray-I (B)	mg/kg	66.43[a]	57.77	47.46	8.67	31.19	92.07
P-Bray-I (A)	mg/kg	75.12[a]	72.44	51.77	9.45	38.03	101.56
K-exch (B)	mmol/kg	1.46[a]	1.38	0.81	0.15	0.78	2.01
K-exch (A)	mmol/kg	1.46[a]	1.52	0.81	0.15	0.79	2.09
P-Olsen (A)	mg/kg	43.56	39.69	32.01	5.84	19.41	65.00

[1] Means followed by different letters within one variable differ significantly ($P < 0.05$).

Input variables

Descriptive statistics for the nutrient inputs added by the farmers in the RF and in the TP during the experiment are given in Table 3.2.

Table 3.2. Descriptive statistics for the nutrient inputs (kg/ha) used in this analysis. n = number of observations, SD = standard Deviation, SE = standard error.

Variable	n	Mean	Median	SD	SE	1st Quantile	3rd Quantile
Tephrosia plots							
Tephrosia N fixed	30	41	24	43	8	18	46
N added with urea	30	92	92	0	0	92	92
Regular Fields							
Organic N inputs	29	229	185	186	35	115	266
Organic P inputs	29	32	18	30	6	14	47
Organic K inputs	29	405	319	359	67	190	462
Inorganic N inputs	29	39	34	30	6	18	44

Inputs added in RF varied to a large extend, as farmers have access to and make use of different amounts of mulch and fertilizers. In general, more N in organic than inorganic form is added, because fertilizer is most commonly only provided as governmental support and it is not bought. Inputs of K vary a lot, but in almost all farms they are higher than inputs of P and N. The average N:P:K in the added inputs (organic and inorganic) in RF is 12:1:15, which makes P the least available nutrient and K the most abundant. The very high K added could compensate for the very low K in the soil, whereas a lack of P could create problems.

TP received only equal amounts of inorganic N as urea and organic N as Tephrosia mulch at quantities that varied according to the biomass production of the shrub on each plot, but where always much lower than the N inputs in the RF.

Organic sources have first to decompose and become available to the tree, therefore these numbers do not necessarily reflect the real effect on yield.

Yield data

Descriptive statistics for the yields recorded in the RF during years 2012-2016 and in the TP in 2016 are given in Table 3.3. Yield gaps were apparent in most fields in the RF and the TP as the potential yield (Y_{max}) was determined at 4500 kg/ha. Only 4 fields achieved a yield close to the Y_{max} even though only for one or two years.

Table 3.3. Descriptive statistics for the yields (kg parchment/ha at 2000 trees/ha) of regular fields (RF) and Tephrosia plots (TP) used in this analysis. n = 30, SD = standard Deviation, SE = standard error.

Variable	Mean	Median	SD	SE	1st Quantile	3rd Quantile
Yield RF 2012	2098	1785	890	163	1494	2800
Yield RF 2013	2227	2097	811	148	1548	2736
Yield RF 2014	2228	2097	874	160	1650	2660
Yield RF 2015	2226	2147	756	138	1680	2800
Yield RF 2016	2237	2219	910	166	1476	2663
5-Year Average RF Yield	2203	2126	696	127	1571	2681
Yield TP 2016	2700	2688	850	155	2078	3249

Multiple linear regression that aimed to predict observed yields (RF and TP) based on soil variables was not significant (model details for the RF: $F_{5,26}$ = 1.07, p = 0.4, R^2 = 0.17, yields = 6484.7 – 787.8*pH – 28.9* SOC + 123.8*TN + 1.4*P-Bray-I + 56.9*K-exch and for the TP: $F_{5,26}$ = 0.71, p = 0.6, R^2 = 0.12, yields = 6485.2 – 826.1*pH – 3.2*SOC + 63.5*TN + 3.6*P-Bray-I + 278.2*K-exch), thus the indigenous soil supply was not a significant predictor of observed yields, which is logical as farmers apply nutrient inputs that could compensate soil limitations.

Nevertheless, observed yields were not explained by the nutrient inputs either. The fitted regression model with observed RF yields as dependent variable and input variables (organic and inorganic N (N), organic P (OP) and organic K(OK)) as predictors was not significant (model details: $F_{3,25}$ = 0.26, p = 0.85, R^2 = 0.03, yields = 2190.4 – 1.7*N – 2.1*OP + 1.1*OK). Thus, the inputs are not balanced in terms of N, P, K. The limiting nutrient and the one in excess differ per farm. For the TP, total applied N (organic and inorganic) was not a significant predictor of yields ($F_{1,28}$ = 0.12, p = 0.73, R^2 = 0.004, yields = 2646.6 +1.3*N).

Model testing and improving

Sensitivity analysis

Soil variables

In general, the comparison of the "poor", "average" and "rich" curves shows that the richer the soil, the higher the acquired yields (the curve moves upwards), reflecting larger supply of nutrients (Fig.3.1a-d).

The effect of pH on the model is complicated. An increase in pH brings yield up to an "optimal" point, after which it will decrease. The model assumes that the potential supply of N (SN) is positively correlated to pH, while that of K (SK) is negatively correlated to pH. The relationship of pH and the supply of P (SP) is parabolic. In low pH it is N or P that are limiting the yields. When pH increases, SN and SP increase, but SK decreases. Soon a point is reached that SK has decreased to a limiting level. Also, SP reaches its maximum and from then on starts decreasing. Hence, at higher pH values, the SK and SP decrease, thus yields reduce.

The optimal point depends on the relative availability of the nutrients. If for example K is in excess, it takes longer until it becomes limiting. This can be seen in Fig.3.1a. The curve of the "extra K" scenario has its optimal at higher pH values than the “average” scenario. On the other side, the peak of the “Rwanda” curve (where K is almost 10 times less than N) lies at the left of every other peak.

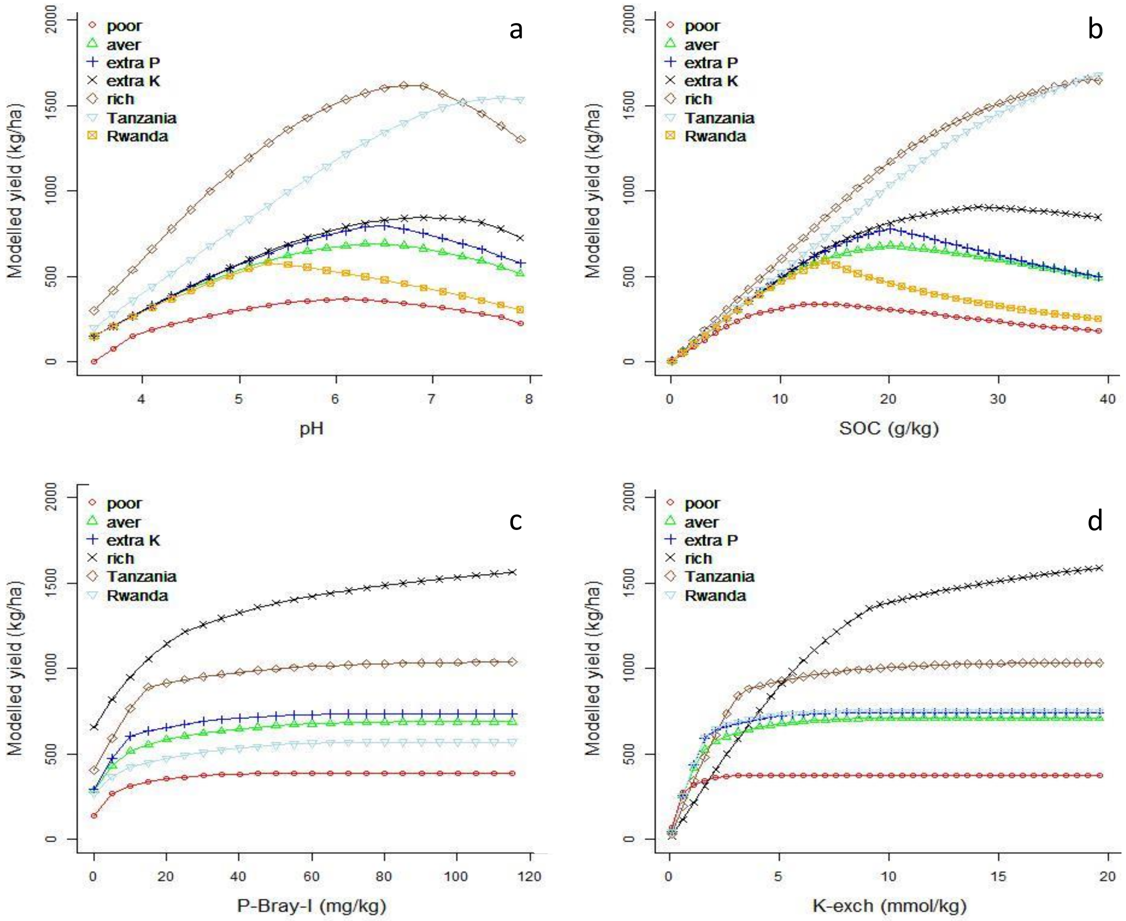


Figure 3.1a-d. Sensitivity analysis of the model to pH (a), SOC (b), P-Bray-I (c) and K-exch (d).

Similarly, by model construction, SOC affects SN and SP positively and SK negatively. Thus, increase in SOC will increase yields up to the point that SK is limiting. Further increase of SOC, will reduce SK with similar effect on the yield (Figure 3.1b). The more K exists initially in the soil in relation to the other nutrients, the more the peak moves to the right (e.g. “average” or “extra P” and “extra K”) as it takes longer to decrease the SK to limiting levels.

Increase in P-Bray-I and K-exch affects only SP and SK respectively. Therefore, yields will keep on increasing until one of the other two nutrients will become limiting (Figure 3.1c-d). Then, the nutrient in excess will be taken up until the point of accumulation, thus yields will slightly increase and eventually a plateau will be reached. Richer soils achieve higher yields, however, relatively high availability of one (or two) nutrients in comparison to the third, will not have positive effects.

Input variables

Table 3.5 presents the results of the sensitivity analysis to the INPUT variables, as well as the modelled potential supplies (indigenous soil supply and input supply) and actual uptakes with 150 kg of nutrient addition, which help identify the most limiting nutrient in each run.

The addition of organic K, P or their combination results in very small yield response. This is because N is the most limiting nutrient in this case. When 150 kg of organic or inorganic N is added, the yield increases, but when 300 kg are added, the increase is smaller, as another nutrient starts to become limiting. As the response to addition of NK is larger than that of NP, probably it is K the limiting factor. When 300 kg of all nutrients are provided yields, almost quadruple.

Table 3.5. Model calculated potential supplies of N (SN), P(SP) and K (SK), the actual uptakes (UN, UP, UK) when the model is run with the addition of 150 kg of various nutrients or their combinations and the modelled yields when 150 kg or 300 kg of nutrients are applied. Cells in red indicate the most limiting nutrient.

Inputs	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)	Yield (kg/ha)	
							150 kg	300 kg
None	35.6	13.9	54.7	35.3	11.8	48.8	620.5	
ONN	83.5	13.9	54.7	77.6	13.0	53.4	905.4	1000.0
INN	115.4	13.9	54.7	102.0	13.0	53.4	972.2	1082.3
INP	35.6	25.3	54.7	35.3	17.2	48.8	675.9	688.4
INK	35.6	13.9	134.5	35.5	11.8	88.2	701.6	708.5
INN-INP	115.4	25.3	54.7	102.0	21.3	54.3	1107.5	1254.0
INN-INK	115.4	13.9	134.5	106.1	13.7	117.8	1290.0	1536.8
INP-INK	35.6	25.3	134.5	35.6	17.2	88.2	738.2	748.1
INN-INP-INK	115.4	25.3	134.5	112.5	23.7	125.1	1663.3	2649.0

The above results indicate the expected model behaviour, i.e. increase in yields with addition of nutrients, with stronger response when the most limiting nutrient is added.

Physiological efficiencies

The model is more sensitive to the physiological efficiency (PhE) of the nutrient that is most limiting. In an 'average' soil, N is most limiting (Table 3.6), thus the yields change 10 – 40% when efficiencies are adjusted (Table 3.7). On the other side, in the Rwandan soils, K is the limiting nutrient (Table 3.6), which increases the sensitivity of the model to the related variables (Table 3.7). The nutrient efficiency at dilution creates the strongest model response as it is determining the upper limit of the yield range allowed in Step 3 of the model.

Table 3.6. Model calculated potential supplies of N (SN), P(SP) and K (SK), the actual uptakes (UN, UP, UK) and the final yield when the model is run with an average soil and with a soil of the testing region. Cells in red indicate the most limiting nutrient.

Soil	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)	Yield (kg/ha)
Average	35.63	13.89	54.72	35.30	11.79	48.81	620.5
Rwanda	35.63	29.09	27.36	33.72	16.35	26.49	569.1

Table 3.7. Modelled yields (kg/ha) when physiological efficiencies are doubled or halved in an average soil and in a soil of the testing region and % yield change compared to the yield calculated with the default values (620.5 kg/ha and 569.1 kg/ha respectively).

Variable	Doubled		Halved	
	Modelled yield	% change	Modelled yield	% change
	Average soil			
aN	689.8	11	586.4	-6
dN	780.4	26	374.6	-40
aP	683.3	10	554.3	-11
dP	621.5	0	601.3	-3
aK	686.1	11	566.3	-9
dK	630.3	2	555.0	-11
	Rwandan soil			
aN	614.0	8	541.6	-5
dN	584.3	3	360.6	-37
aP	569.8	0	511.3	-10
dP	568.3	0	569.8	0
aK	594.0	4	552.9	-3
dK	642.2	13	324.5	-43

Elasticity analysis

The elasticity indices show the differing model response according to the soil conditions and inputs used to run it (Fig.3.2). When no inputs are added ("Tanzania", "Rwanda", "Average") the model is more sensitive to the most limiting nutrient (N for "Tanzania", K for "Rwanda" and N and P for "Average") (Table 3.8).

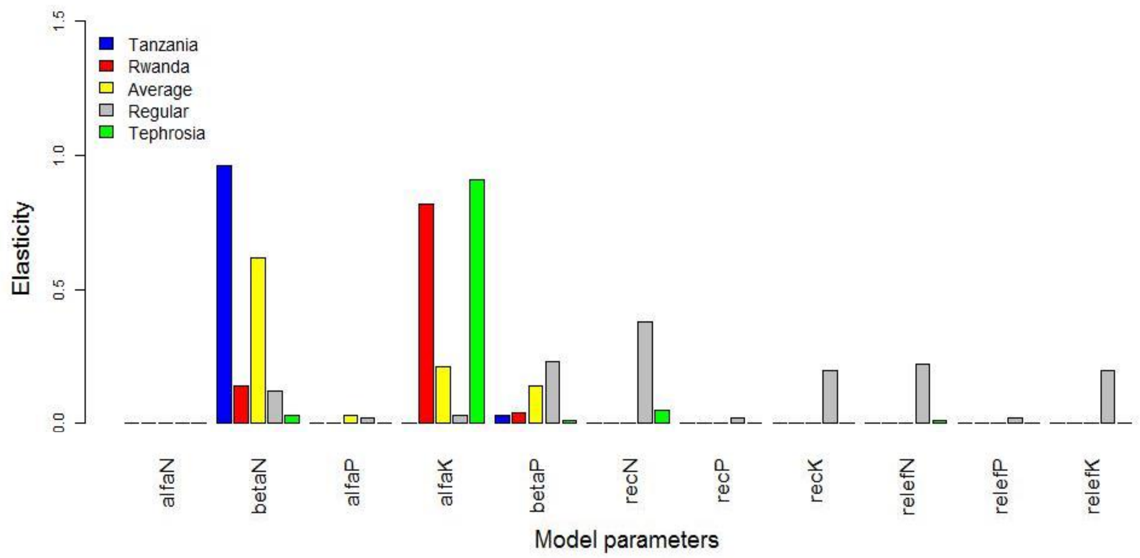


Figure 3.2. Elasticity analysis of the model to its parameters.

With addition of inputs, the same conclusion is drawn, i.e. sensitivity to the parameters of the most limiting nutrient is noticed in the model behaviour. In scenario "Regular", enough K is added so it is not limiting anymore and the model sensitivity to the respective variables weakens. When inputs according to the TP are added (only N from the fixation and the urea fertilizer), it is K that limits yields, therefore the model responds strongly to those parameters.

Table 3.8. Potential supplies (SN, SP, SK) and actual uptakes (UN,UP,UK) of the three nutrients as calculated by SAFERNAC with the default SOIL and INPUT variables used in the elasticity analysis.. Cells in red indicate the most limiting nutrient(s).

Scenario	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)
Average	35.62	13.89	54.72	35.29	11.79	48.80
Maro	53.20	34.12	255.30	53.20	24.43	139.50
Rwanda	53.20	34.12	25.53	47.12	15.32	25.33
Regular	168.52	36.42	217.74	164.09	34.17	199.67
Tephrosia	114.53	34.12	25.53	79.24	15.32	25.53

In conclusion, the parameters that trigger the model response are the ones related to the most limiting nutrient, as expected.

Model evaluation

The graphical model evaluation is shown in Figure 3.3 and the goodness-of-fit measures in Table 3.9. In general, the agreement of the modelled and observed yields is low, with an RMSE value of 1.842 kg/ha. The model is obviously underpredicting yields, as most of the datapoints fall under the 1:1 line (Figure 3.3), which indicates low accuracy. Additionally, the scatter is extended, which underlines low precision. All these are quantified by the higher MSE_{sys} in relation to MSE_{unsys} when all data are considered.

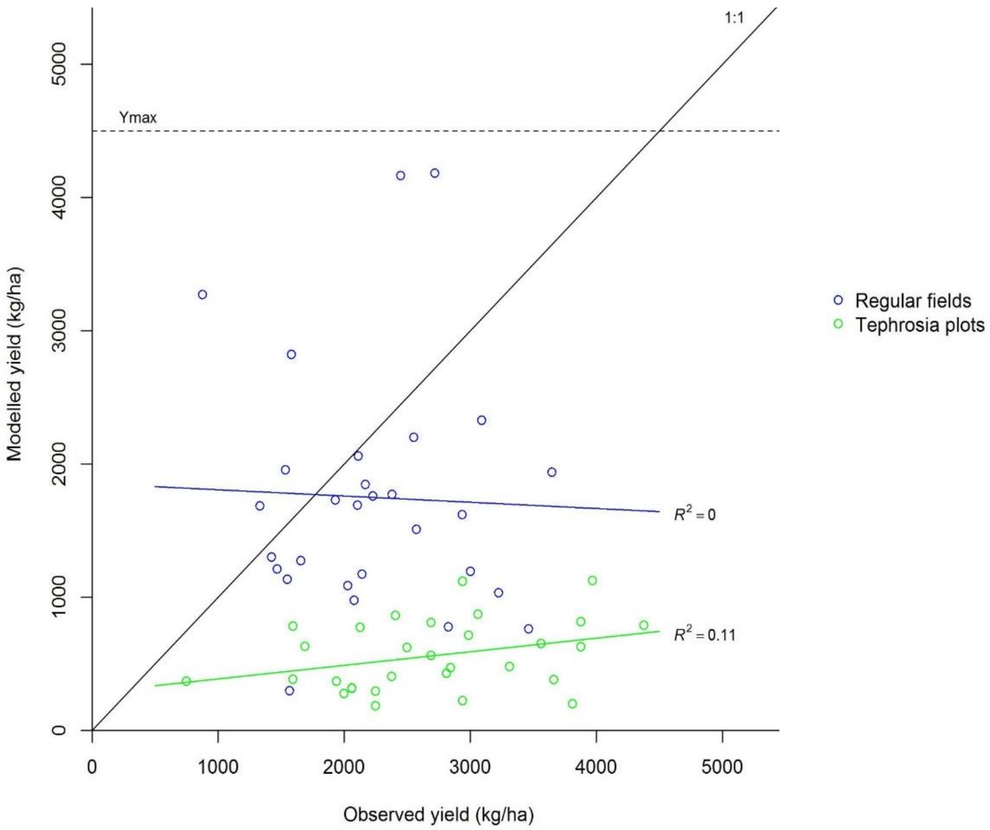


Figure 3.3. Graphical model evaluation with the data from the TP and the RF.

The TP and RF data are clearly separated in the graph (Fig. 3.3). Data of RF fall closer to the 1:1 line than that of TP (higher accuracy), with some falling on the 1:1 line, a few being over estimated by the model and most underestimated. However, the scatter is large (low precision). The variation in modelled yields (300 – 4200 kg/ha) is slightly larger than the variation in observed yields (900 – 3700 kg/ha). This creates the large MSE_{unsys} value.

Data from the TP are clustered on the lower right part of the graph, indicating low accuracy (high bias), depicted in the very high MSE_{sys}. On the other side, precision is improved. The variation in modelled yields (200 – 1200 kg/ha) is much lower than the observed yields (750 – 4400 kg/ha). The scatter is smaller than in RF, which is reflected in the relatively low MSE_{unsys}, almost 13 times smaller than when the RF are used in the analysis.

Table 3.9. Measures of accuracy (MSE = Mean Square Error, MSE_{sys} = Systematic part of MSE, MSE_{unsys} = Unsystematic part of MSE, RMSE = Root Mean Square Error)

Dataset	**MSE (kg/ha)^2**	**MSE_{sys} (kg/ha)^2**	**MSE_{unsys} (kg/ha)^2**	**RMSE (kg/ha)**
All data	3,394,902	2,633,492.9	761,409.0	1,842.53
Regular fields	1,540,542	736.871.2	803,670.6	1,241.19
Tephrosia plots	5,187,450	5,128,372.7	59,077.3	2,277.60

The potential supplies and actual uptakes of the nutrients are shown in the Appendix 3.2 and 3.3. The most limiting nutrient for the RF was P, followed by N. On the contrary, the SK was often much higher than its uptake. For TP, the limitation was K, followed by P. N was most of the times in excess.

Error exploration

Plotting of the residuals against the predicted yields did not reveal any patterns that could explain the origin of the error. Therefore, these plots are only given in the Appendix 3.4, for reference.

Model calibration

The average $RMSEP_{val}$ from the bootstrapping was 1035.39 kg/ha, with standard error 42.3 kg/ha and confidence interval 993.1 – 1077.7 kg/ha, but the distribution is not normal ($W=0.96$, $p < 0.05$). The calibrated parameter values are shown in Table 3.10. The model evaluation plots in every step of the calibration with the RMSE and R^2 scores are shown in Appendix 3.5. The final plot is shown in Fig.3.4 (left).

The physiological use efficiencies of all nutrients are increased to the maximum values allowed (Table 3.10). To achieve yields as high as observed, the tree has to be efficient in its use of the taken up nutrients. The supply coefficients are higher than original for P and K, but lower for N, indicating the surplus of N availability in comparison to the other nutrients.

Table 3.10. The original and calibrated values of the parameters (only changed values are shown).

Parameter	Original value	Calibrated value
aK	8.0	18.0
dK	24.0	102.0
aN	7.0	20.0
dN	21.0	84.0
recN	0.7	0.5
relefN	0.6	0.4
alfaK	400.0	450.0
alfaP	0.25	0.4
betaP	0.5	0.8
betaN	5.0	10.0
alfaN	50.0	20.0

The final $RMSE_{cal}$ acquired from the calibration (1184.8 kg/ha) is almost half than before the calibration (2277.6 kg/ha, see Table 3.4). The MSE_{sys} = 797,482.6 $(kg/ha)^2$ and MSE_{unsys} = 606,260.2 $(kg/ha)^2$, which indicate that the bias observed in the original model has been removed (Table 3.9, Fig.3.3), but the unsystematic error (scatter) has increased (Fig.3.4).

Final model evaluation

The final graphical evaluation of the model with the independent set of RF (Fig. 3.4, right) shows that more than half of the farms fall around the 1:1 line, but at least 30% reaches the Y_{max} (4500 kg/ha). All RF modelled yields are higher than before the model calibration. The goodness-of-fit measures (RMSE = 1816.4 kg/ha, with MSE_{sys} = 1,986,962.1 $(kg/ha)^2$ and MSE_{unsys} = 1,312,384.0 $(kg/ha)^2$) score higher than the original model. Both bias and scatter are larger than the initial model evaluation.

The modelled potential supplies and actual uptakes for each farm are shown in Appendix 3.6. The farms appear to be separated in two groups, one that reaches the maximum yield (4500 kg/ha) and one that is scattered around the 1:1 line. The farms that achieve the Y_{max} is not limited by any nutrient (Appendix 3.6). The others, are mostly limited by low P, or sometimes N supply, like in the initial model evaluation. The relative availability of the nutrients did not change, but all amounts were higher than in the initial evaluation due to the adaptation of the parameters.

Because the physiological efficiencies for P have also increased, the yields gains are rapid. In particular, the $PhEP_D$ is 120 kg/kg, hence for every 1 kg P taken up, when SP is smaller than SN and SK (when it is limiting), 120 kg of extra yield is produced by the tree. Similarly for N, which also approaches the dilution level and the calibrated $PhEN_D$ is 84 kg/kg. Combined, the additional uptakes of the two limiting nutrients were translated into significant yield improvements.

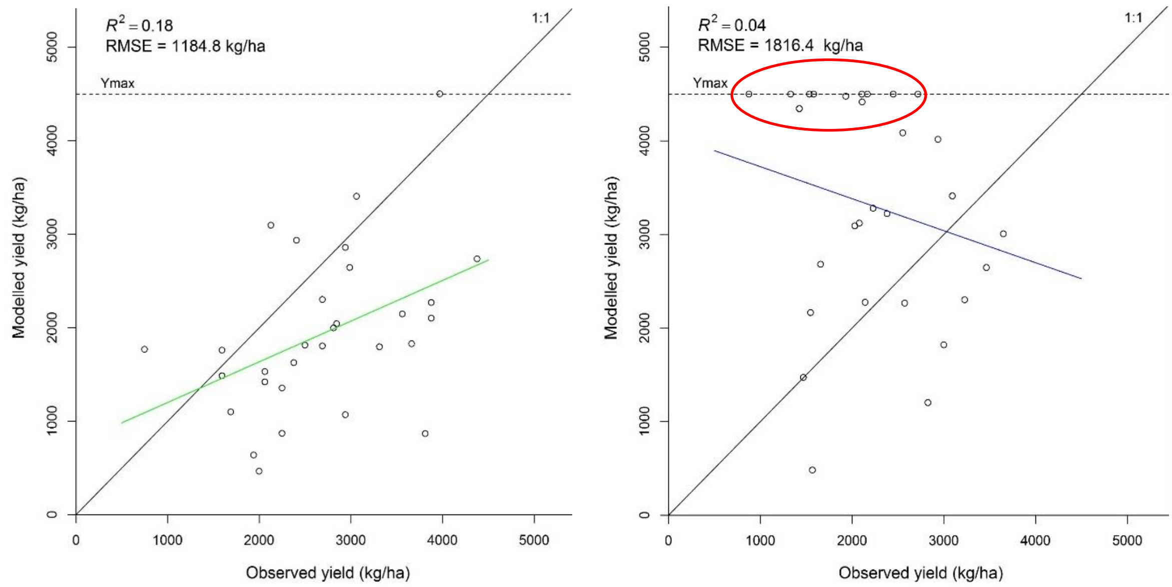


Figure 3.4. Model evaluation with the training set (TP) after the last step of the calibration (left) and with the evaluation set (RF) (right). The green and blue lines indicate the fitted models. The red circle indicates the fields that reach the maximum yield (4500 kg/ha).

Nutrient management with the SAFERNAC model

Common nutrient management practices and tree maintenance

According to the information recorded from the interviews in relation to common management practices, all farmers were reported to mulch, with different materials and quantities. All farmers have mentioned to use *Pennisetum sp.* as mulch. Maize residues is the next most common organic source of nutrients, used by 77% of the farmers. Bean residues are applied by 63% of the farmers, compost is applied by 59%, manure by 52% and banana leaves by 52% of the farmers. More materials are used as mulch by a smaller number of farmers and they are presented in Table 2.1 along with the nutrient composition.

Fertilizer is applied by 92% of the farmers, always in November. Available quantities are always limited, thus its distribution to the trees varies per farmer; either it is spread rotationally, or in smaller quantities but on larger areas, or it is given to productive trees, or to trees that seem weaker.

The mulching always takes place at least once in June after the harvest but half of the farmers reported a second time, around February, when other crops are harvested and residues become available. Mulch is never enough for all fields, thus, various strategies are used to manage the available quantities. For example, 22% of the farmers spread a thinner layer of mulch trying to cover all fields, 22% prefer to take care of lower-producing trees first and some 18% of them follow rotational mulching, i.e. every year they mulch different (parts of) fields in a rotational manner. The remaining 38% has other strategies, or divides the materials at random.

Additionally, every farmer reported to weed the coffee trees, but in varying frequencies. One quarter of the farmers weeds 3 - 4 times a year, one quarter every month and the rest follow varying strategies. The weeds are always left on the field as mulch.

Finally, pruning is performed by all farmers at least once in June after coffee harvesting. At least one more moment was reported by 85% of the farmers. Additionally, approximately 60% coppice all their trees every 5 - 6 years. The fresh, green parts and the leaves are left on the field, while brown parts are almost always used as firewood for cooking.

Assessment of Tephrosia intercropping

The comparisons of the soil variables from before and after the Tephrosia intercropping are depicted in Fig. 3.5. Only pH and SOC were found to differ before and after the establishment of the experiment. Particularly, pH (A) (M=5.61, SE=0.06) was significantly higher than pH (B) (M=5.5, SE=0.05), ($t(29)=4.2$, $p<0.05$). SOC (A)

(M=19.9, SE=1.32) was also significantly higher than SOC (B) (M=15.8, SE=1.28) (W=115, P<0.05). TN, P-Bray-I and K-exch before and after did not significantly differ (t(29)=0.9, P=0.37, W=204, p=0.57 and W=228, p=0.93 respectively. For means and standard errors, see Table 3.1).

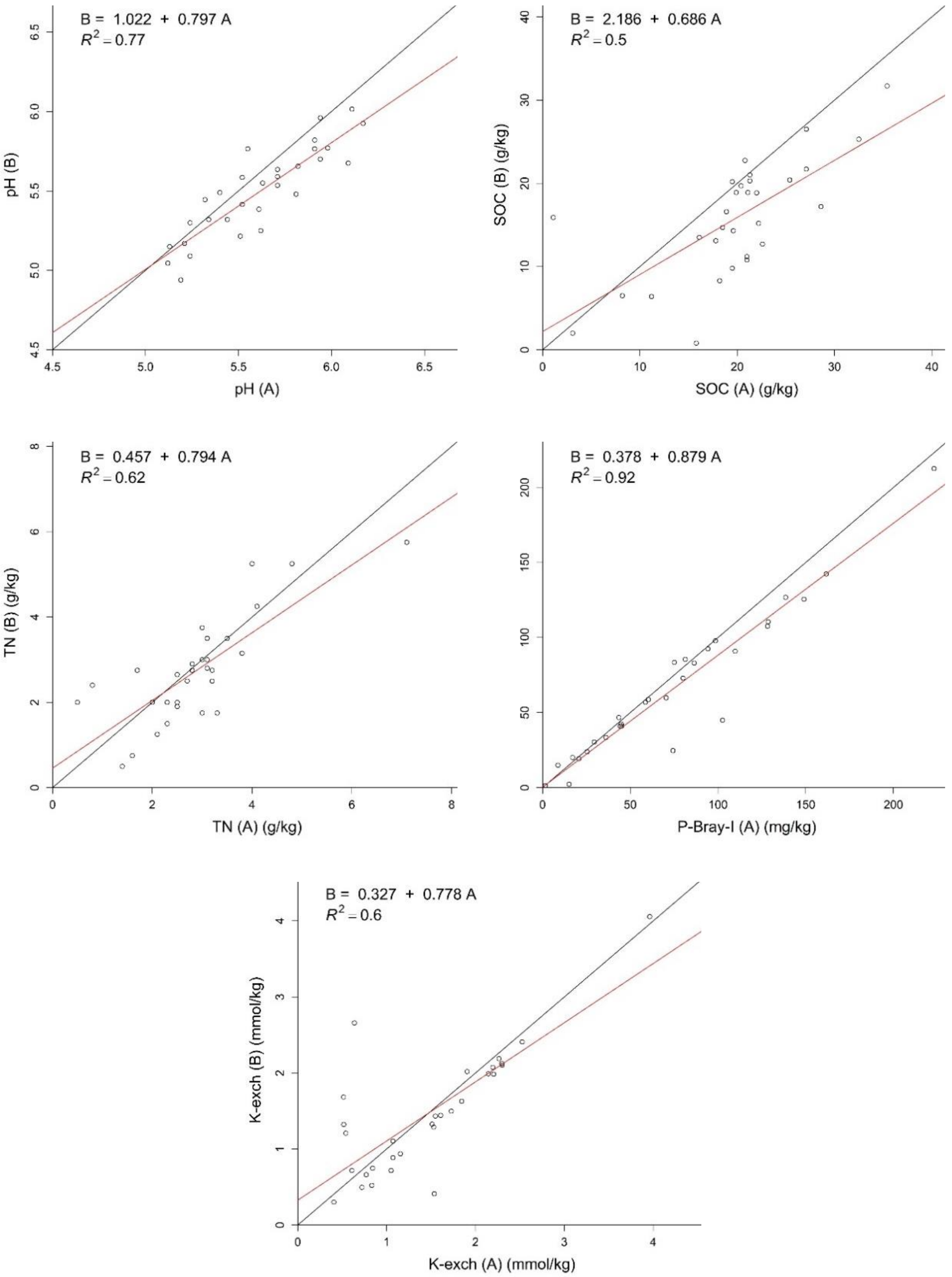


Figure 3.5. Correlations between soil fertility variables before (B) and soil fertility variables after (A) the establishment of Tephrosia.

Modelled yields without inputs on average reduced (M = 1708.6 kg/ha, SE = 156.0) when Tephrosia is intercropped with coffee (M = 1593.3 kg/ha, SE = 146.5), but the effect was not statistically significant (W = 308, p = 0.12) (Figure 3.11). The yields were significantly correlated (r_s = 0.58, p < 0.05).

On average, observed yields of 2016 in TP (M = 2700 kg/ha, SE = 155.0) were significantly higher than the across-years average RF yield (M = 2203 kg/ha, SE = 127.0) ($t(28) = 6.96$, $p < 0.01$). However, when modelled, the RF yields (M = 3302 kg/ha, SE = 220.9) were significantly higher than those of TP (M = 1941.6 kg/ha, SE = 159.6) ($t(28) = 6.7$, $p < 0.01$). The modelled yields were also significantly correlated ($r = 0.49$, $p < 0.01$).

For most farms, intercropping with Tephrosia increased yields (Fig. 3.6). Particularly for fields with low yields, Tephrosia had a positive effect, while among the ones that achieve higher yields, the shrub often had a negative effect (e.g. Fields 5, 2, 17). This analysis also revealed variation in yields across the years was observed for almost all regular fields (except 22, 12 and 11), even though for some this was more pronounced (e.g. fields 20, 7). Some fields seemed to consistently have lower yields across different years (e.g. fields with number 20, 28, 3), while others maintain high yields (e.g. fields 7, 5, 16) (Fig.3.6).

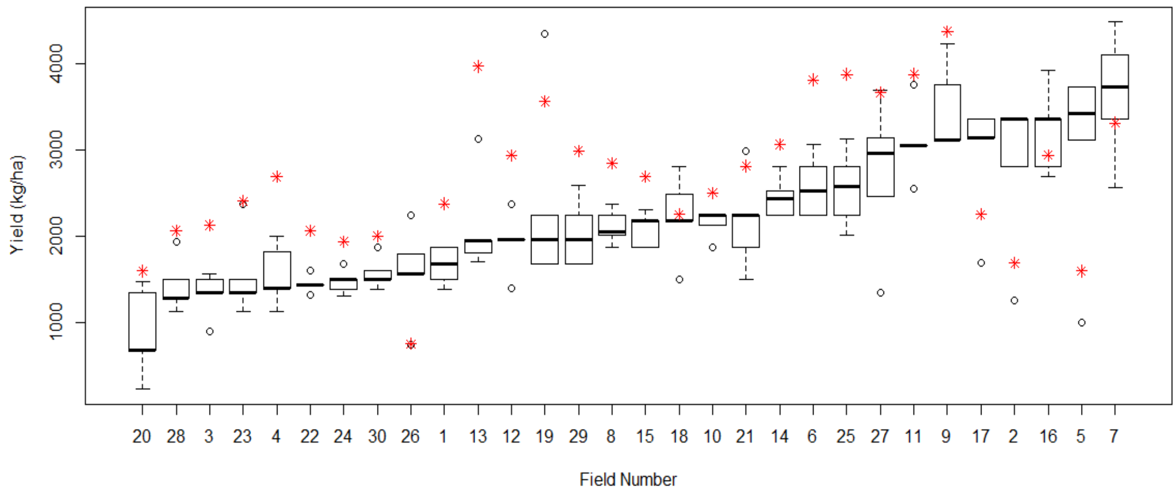


Figure 3.6. Variation in observed yields (kg/ha) of RF per farm across years 2012-2016. Fields are sorted according to the median. Red stars show the TP yields of 2016.

Comparing common nutrient management practices

The modelled yields achieved with different types and amounts of nutrient sources are presented in Fig. 3.7.

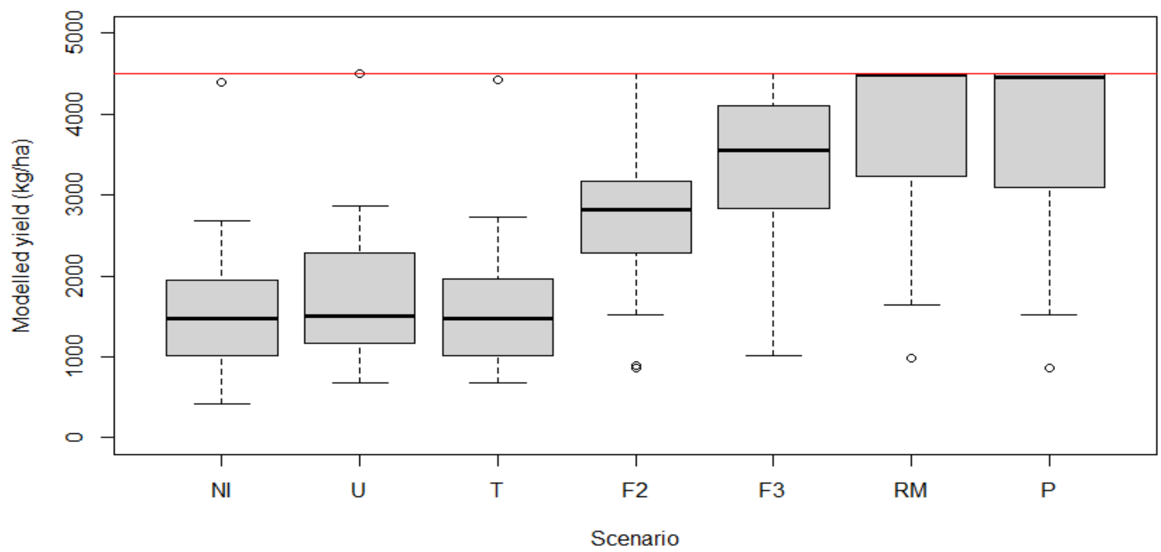


Figure 3.7. Comparison of yields acquired under different fertilization options. (NI=zero inputs, U=urea 46%, T=Tephrosia mulch, F2=NPK 17-17-17 plus urea 46%, F3=NPK 20-10-10, RM=Regular Management, P=Pennisetum sp. For application rates see text). Red line indicates the Y_{max}.

Urea alone and Tephrosia increase yields only by 8% and 9% respectively, which is expected, as the K limitation is not overcome. Similarly, with F2 (NPK + urea) yields increase because K is added, but when K becomes limiting, the additional N is in excess. In the case of F3 the importance of providing a balanced combination of nutrients is remarked, as this fertilization option leads to doubling of the yields. Finally, the use of organic materials, i.e. *Pennisetum sp.* seems to be the best way to increase yields in most farms, but the fact that almost half of the farms reach maximum yields implies application of nutrients in excessive quantities.

The agronomic efficiency (AE) (Table 3.11) gives important additional information. The AE of urea and Tephrosia are very low because the yield improvement is very small. Use of mineral fertilizers appears as most efficient in comparison to organic sources, despite the smaller effect on yield (Fig. 3.7). This is explained by the excessive amounts of nutrients applied as organic sources, in comparison to inorganic and their N:P:K ratio.

Table 3.11. Nutrient inputs (total = organic and inorganic) per scenario in kg and kCNE and the agronomic efficiency (AE) per nutrient and for the total amount of nutrients (averaged for all farms, in kg coffee/kCNE nutrient). na = not available because calculation not possible. For N it holds that 1 kg = 1 kCNE. For scenario abbreviations see Fig.3.8.

Scenario	**N_{total}**	**P_{total}**		**K_{total}**		**AE_N**	**AE_P**		**AE_K**		**AE_{total}**
		kg	**kCNE**	**kg**	**kCNE**		**kg**	**kCNE**	**kg**	**kCNE**	
U	92.0	0	0	0	0	1.43	na	na		na	1.43
F2	109.8	17.8	11.6	33.8	29.3	9.88	60.8	93.63	32.0	36.97	7.20
F3	160.0	34.9	22.7	66.4	57.5	10.60	48.5	74.61	25.5	29.46	7.05
T	40.8	0	0	0	0	0.75	na	na	na	na	0.75
RM	267.3	32.3	21.0	405.8	351.7	7.98	66.1	101.72	5.2	6.06	3.33
P	236.4	16.8	11.0	462.0	400.4	8.71	122.6	188.57	4.5	5.14	3.18

Farms often use all the mulch they have access to, often using residues from other fields depleting their potential. This is inefficient use, as when maximum yield is achieved, the remaining nutrients will not be taken up and be lost, evidenced by the low AE values.

Fertilization recommendations for target yields

The simulation of a fertilizer trial with the aim to identify the nutrient combinations in order for each farm to achieve the target yield of 4000 kg/ha is shown in Table 3.12. The most optimal choice differs per farm and can be found in Appendix 3.7.

Table 3.12. Number of farms achieving the target yield of 4000 kg/ha with the applied nutrient combination.

Treatment			**Number of farms**
N (kg/ha)	**P (kg/ha)**	**K (kg/ha)**	**achieving target yield**
0	0	0	1
300	0	0	2
0	450	0	1
0	0	300	14
300	450	0	2
300	450	100	28
300	450	150	28
300	0	300	18
300	150	300	23
300	300	300	26
300	450	300	30
0	450	300	25
100	450	300	27
200	450	300	29

For almost half of the fields, addition of 300 kg/ha of K is sufficient to achieve the target yield. Apparently, the soil indigenous supply for N and P is sufficient and K is their only limitation.

If only N or P is added, or their combination (NP), yields might respond, but the target yield is not reached. Addition of K together with only N (300 kg/ha) assists 60% of the farms to achieve the goal, but appears to be on average the worst combination. K (300 kg/ha) plus only P (450 kg/ha) already ensures that 80% of the fields are successful. The combination of all three nutrients at rates of 300 kg N, 450 kg P and 300 kg K works for all fields, even though this should not be interpreted as the optimal strategy. The amount of required P (450 kg) is so large due to its very low recovery fraction (= 0.1). Other combinations are possible and are case-specific. Each farmer can identify his/her own optimal plan.

Discussion

Model performance

General conclusion on model performance

SAFERNAC's predicting ability in Rwandan farms, even after the calibration, was found insufficient. Due to its empirical nature, SAFERNAC was expected to present lower accuracy in conditions different than in Tanzania, where it was developed and that calibration would be required to improve its fitness (Dourado-Neto et al., 1998).

The Rwandan farms differed in terms of soil conditions and management from the Tanzanian experimental fields (Maro et al., 2014a, 2014b). Particularly, K-exch levels were on average approximately 10 times lower than the development conditions, while all variables contained values that fell out of the original range or even exceeded the boundary conditions, as discussed in Maro et al. (2014a). It is notable that the P-Bray-I values of the Tanzanian soils did not satisfy the respective model assumption either. The calibration allowed the adaptation of the conditions where the model can be used, however, its performance remained poor.

The initial assessment with the data from the regular fields (RF) showed large scatter, but better accuracy than the Tephrosia plots (TP). This is due to the compensation of the low soil K levels in the RF through the farmers' mulch, while TP receive only N inputs. The evaluation with the TP data at first glance seemed precise, though inaccurate, therefore the TP were chosen for the calibration of the model. However, after that the bias reduced, but the scatter increased. Due to the fact that the model calculations are largely determined by the most limiting nutrient, in this case K, the variability of N inputs in the TP were initially not sufficiently expressed in the model outcome. When K limitation was lifted by adjusting the relevant parameters, the varying quantities of N additions in the TP were expressed lowering the initial precision.

Eventually, the R^2 acquired with the training set was almost 0.2. However, real evaluation requires data from independent fields (Wallach et al., 2014). If the same dataset is used for training and evaluation, the model's fitness will be overestimated. The R^2 calculated with the evaluation dataset was 0.04, indicating practically lack of any predicting ability of the model. The R^2 of 0.9 that Maro et al. (2014a) reported at the development of SAFERNAC is high, but it was based on an evaluation with the training set (B. Janssen, 2017, personal communication).

Explanation of the poor accuracy of the model, can be seeked in the two main sources of error according to Loague and Green (1991): error in the input variables or in the model itself.

Measurement error in the data

The scatter in the model evaluation was interpreted as noise resulting from yield estimating procedures. The soil and input data in this study were most likely to show high measurement error. Observed yields were not expected to entail a large amount of error because the TP yields are monitored by the experiment and the RF yields are recorded by the coffee washing station when the product is bought by the farmers. Finally, the values of the physiological efficiencies might be inaccurate, as they were based on literature data.

The reliability of the soil data can be questioned due to the problems with the laboratory analysis of the control sample. Nevertheless, similar soil chemical fertility values have been recorded in Rwanda before. pH values lower than 6.5 (Nzeyimana et al., 2013; Verdoodt and Ranst, 2003), and even less than 5 (Bucagu et al., 2013) have been measured. The levels of SOC in Acrisols, Ferralsols and Alisols agree with their characterisation as "Humic" and fit the estimations of less than 10% SOC (100 g/kg) in many Rwandan soils (Nzeyimana et al., 2013) as well as reported values of 6.5 - 23 g/kg in Southern Rwanda (Bucagu et al., 2013). K-exch levels lower than 5 mmol/kg (Bucagu et al., 2013) or even 2 mmol/kg have also been reported (Mukuralinda et al., 2010; Nzeyimana et al., 2013). K depletion can also be explained by the land use of coffee growing, which is a K-demanding crop (Wrigley, 1988), as 1 ton of harvested coffee beans can remove 63.6 kg N, 12 kg P and 87.3 kg K (Nair, 2010).

On the other side, P-Bray-I levels were slightly higher than the 4.4 - 13.1 mg/kg levels mentioned by Bucagu et al. (2013) and common values in the country of less than 20 mg/kg (Nzeyimana et al., 2013). Finally, the average TN value was slightly higher than what Bucagu et al. (2013) found (0.8 - 1.7 g/kg) and the general statement of Nzeyimana et al. (2013) about Rwandan soils containing up to 1.6 g/kg TN.

The error in the nutrient input data of the RF could be a result of the use of interviews as collection method of the applied quantities, the retrieval of the nutrient content of each material from the literature, or the simplifications made during the calculations. The response error during the interviews (Fermont and Benson, 2011) could be expressed either by providing incorrect information, or omitting some information all together, especially due to the increased time gap between mulch application and interviews (Beegle et al., 2012). Furthermore, the transformation of quantities of organic sources into nutrient amounts based on literature data is likely to be responsible for errors, mainly due to the large variability of such values. Using literature values of mass fractions is common (e.g. (Kanté et al., 2007; Smaling and Janssen, 1993; Tittonell et al., 2005)), however often authors do not justify the choice and do not discuss implications on their results. Finally, the decomposition process, which determines nutrient availability, was not determined according to the input quality, but calibrated as the parameter of relative effectiveness included in SAFERNAC (Maro et al., 2014a).

Tephrosia biomass applied on the intercropped plots was measured during the experiment and it was expected to be largely accurate, thus, the uncertainty is limited to the amount (if any) of N fixed, which was the only input considered in these plots. N inputs from fixation by Tephrosia were on average 41 kg/ha which is significantly lower than the amount of 157 kg/ha assumed by Mafongoya et al. (Mafongoya et al., 2006). Rutunga et al. (2008) also found varying Tephrosia growth and N content of 154 kg/ha, which could correspond to 100 kg/ha of fixed N. According to Kwesiga et al. (2003), Tephrosia can produce 1.8 - 4 tons biomass per ha, which corresponds to 35 - 78 kg N fixed per ha. Perhaps these estimations are based on a higher planting density of the shrub.

Also, the root biomass of Tephrosia was not quantified, because the shrub was harvested and the roots were left on the field to decompose. However, fine plant roots can have similar composition to foliage (Berg and McClaugherty, 2008), therefore they can contribute significantly to the total field inputs.

The ratio of N fixed to total N in the plant was set at 65% for all fields. However, the level of fixation depends on many factors, like environmental conditions and other nutrients (Cooper and Scherer, 2012). For example, low pH, like in Rwanda, may be toxic to rhizobia, while a rate of applied inorganic N as low as 20 - 40 kg/ha was found to inhibit N fixation in legumes (Cooper and Scherer, 2012). In the Tephrosia plots 92 kg/ha of N were applied in the form of urea, which is higher than the above mentioned rate. Also, according to Mafongoya et al. (Mafongoya et al., 2006), legumes grown as intercrops might fix less N than when grown alone due to competition with the crop. Finally, the shrub growth differed among the fields, as Giller (1993) mention that poor nodulation and poor growth are related. Therefore, perhaps the percentage of N fixed among different fields differed as well and might have been lower than expected.

The measurement error of the input and soil variables has implications on the calculation of the potential supply of each nutrient and in turn, on the modelled yields and eventually on the model evaluation. The sensitivity analysis showed that the effect of 300 kg applied nutrients can be 50 to almost 2000 kg/ha depending on whether the added nutrient was in excess or not. Major input sources, like maize residues and *Pennisetum sp.*, have a larger effect on the model outcome than materials used on an occasional basis or smaller amounts, like mineral fertilizer. Similarly for the soil available nutrients. For example, in the case of P limitation, additional 20 mg/kg in the soils might allow up to 1000 kg/ha increase in coffee yield. However the magnitude of the implications differs per farm, as the model responds stronger to the most limiting nutrient and less to nutrients in excess, which are determined by the combination of existing nutrient soil stocks and management.

Finally, the adaptation of the model QUEFTS to other crops, like banana (Nyombi et al., 2010), wheat (Liu et al., 2006) and cassava (Ezui et al., 2016) has more often been done successfully. In all these cases the values of the physiological efficiencies were calculated with measurements on nutrient uptake by the crop, yields and on the harvest index, which allowed for step by step parameter estimation. However, in this study literature data were used to correct the values of physiological efficiencies set by Maro et al. (2014a), who did not make plant measurements either. The corrections were based on the maximum possible harvest index and the maximum nutrient concentrations in the plant parts that could be found in the literature. In general, these values depend largely on the genetic basis of the coffee trees and large cultivar-dependent variation is noticed, particularly in terms of N and K (Lima et al., 2015). The exact cultivar grown by the Rwandan farmers or on the Tanzanian fields is unknown and data on nutrient uptakes from coffee trees are hard to find (Cannell and Kimeu, 1971). As seen in the sensitivity analysis, modelled yield can deviate up to 40% when the values of the efficiencies are changed. Therefore, the lack of such data can have implications for the accuracy of the calibration.

Concluding, even though variability is desired for the development of a model with wide application, noise and error in the data, particularly when unsystematic, can hinder the dissemination of patterns, resulting in failure of the model building. Especially, when the sample size is relatively small, as in this study, generalizations might be impossible to make and concerns can be raised over the representativeness of the farm sample of the target population (Fermont and Benson, 2011).

Errors in the model structure

The model structure, i.e. which components are included or excluded, is another factor that could reduce its predictive ability, even with accurate data (Loague and Green, 1991).

SAFERNAC considers yield as a function of only the supplies of three nutrients, N, P, K, while other growth limiting or reducing factors are at optimal levels. However, if other growth factors are actually limiting, the model will capture variation that is not explained by its structure and its parameters, with consequent incorrect yield prediction and inaccurate fertilizer recommendations.

Other growth factors, except soil chemical fertility and management were not checked in this study, but neither in the model development by Maro et al. (2014a). Janssen (2004), where Maro et al. (2014a)'s work was based, mention that the years with the best yields were chosen for the analysis, aiming to ensure that yield was determined by nothing else but the nutrient supply. In this report, yield variation in time and per farm was observed, but no conclusions about the reason can be drawn. During the interviews, all farmers were reported to follow the good management practices (weeding, pruning, mulching), but lack of sufficient nutrient inputs was also always mentioned. Therefore, this was identified as the main limitation.

Another simplification in the model structure is that it does not consider the synchronisation of uptake requirements and mulch application timing. Applied organic sources are multiplied with a parameter that represents their decomposability, thus the fraction of nutrients that become available, but the timing and the nutrient release pattern is not considered at all.

Further concerns regarding the model structure relate to the perennial nature of coffee. QUEFTS was initially developed for maize and has since then been calibrated on other crops, but except coffee, all of them were annuals. The uptake of nutrients could therefore be estimated for one season. In perennials, the nutrient uptake and tree growth in combination with management during one growing season could affect the yield of the following season as well. For example, in coffee, but other fruit trees as well, biennial bearing (Beaumont and Fukunaga, 1958; Wrigley, 1988) is observed. This happens under environmental stress, like lack of nutrients, when the crop of one growing season cannot be supported by the tree because berries function as a very strong sink during maturation. Thus the tree's health is compromised and with it, its ability to bear the crop next year.

Additionally, trees' age, which affects their productivity, is not considered. Especially the first 5-6 years after planting, much of the taken up nutrients can be used for root development (Witt et al., 1999; Wrigley, 1988) instead of berry growth. The age of the studied trees varied from newly planted to 40 years old.

SAFERNAC requires measurements only of topsoil nutrients (0 – 20 cm). Normally, this part of the soil contains the largest amounts of organic matter, thus nutrients (Lehmann, 2003), particularly due to the rapid nutrient cycling in coffee systems through senescence (Cannell and Kimeu, 1971). However, with high temperatures and precipitation, nutrients might leach to the subsoil. On the other side, the coffee rooting system (Wrigley, 1988) is characterised by a main tap root and many feeder roots, whose main activity is noticed on the topsoil. Even though their growth is limited to one meter from the water table and in acidic soils, they are able to penetrate a hardpan gaining access to more nutrients (Rose and Bowden, 2013; Wrigley, 1988). This root morphology can allow access to nutrient stocks that are not considered in the model but can affect yield. This is of particular importance for K, which was found to be very limiting in the topsoil. K is not very mobile in the soil (Rose and Bowden, 2013), but small available subsoil resources might have an effect on yields, given the high physiological efficiency of coffee for K. It is useful to be noted that there have been no evidence of mycorrhizal symbiosis with coffee trees (Wrigley, 1988), which would offer them access to additional P.

A final remark relates to the ability of plants to relocate nutrients (Rose and Bowden, 2013). Cannell and Kimeu (1971) did not find any evidence of K storing by the coffee trees, yet they noticed that coffee branches functioned as P source for nutrient relocation.

The above are a few important variables not included in the model structure that might result in unexplained variation of the yields. It is not meant to be an exhaustive list or even a conclusive discussion, but rather to raise questions for further considerations for the model improvement.

Nutrient management with the SAFERNAC model

Common nutrient management practices

The comparison of actual practices and required inputs can assist in understanding and explaining the yield gap (van Ittersum and Rabbinge, 1997). The first step was to identify common management practices applied by the farmers and the reasons that shape them.

According to a survey among coffee farmers in Rwanda by Loveridge et al. (2002), 65.4% of the farmers interviewed mulch their coffee fields, while only 12.9% use compost and 9.9% use chemical fertilizers. However, all the interviewed farmers of this study claimed to mulch their fields. The materials they use differed according to their access and affordability, but according to them, inputs are never at sufficient quantities. They often use crop residues from their food crops or they grow mulch on the sides of other fields which they then carry to the coffee. Drechsel et al. (1996) also report that land scarcity often drives farmers to growing mulch on field margins. The application of mulch mixtures, practiced by some farmers seems to be beneficial because the varying material quality might result in a better nutritional balance (Nair, 2010). Finally, the use of fertilizer is a top-down solution as farmers use only the amounts that are subsidized by the government, but it is unclear if the reason is unaffordability or inaccessibility. Drechsel et al. (1996) agree that fertilizer use in Rwanda is very low (0.4 kg/ha for arable crops), perhaps due to insufficient availability (Mafongoya et al., 2006).

Assessment of Tephrosia intercropping

Observed yields of RF were significantly lower than those of TP. A positive effect of Tephrosia on coffee yields has also been found by Bucagu et al. (2013) in a similar field trial in South Rwanda. The soils were strongly acidic (pH = 4.6) and poor in N (TN = 1.2 g/kg), P-Bray-I (7.3 mg/kg) and K-exch (5 mmol/kg). Bucagu et al. (2013) observed an increase of 400 - 500 kg/ha in coffee yields when Tephrosia mulch from intercropping was applied on the field in comparison to farmers' mulch, which consisted of 50% of Eucalyptus branches and litter, 20% *Grevillea robusta* branches, 10% of *Hyparrhenia filipendula*, 10% *Sorghum bicolor* residues and 10% banana stems. Its nutrient composition was 1.14% N, 0.09% P and 1.64% K, while the total N in Tephrosia mulch was 4%, even though the amount attributed to N fixation is not specified.

The acquired yields in this study's region (North West Rwanda) were in general higher than what Bucagu et al. (2013) recorded. Probably because the soils were less acidic and richer in TOC, P-Bray and TN, even though K levels were lower. The yield difference found among TP and RF for 2016 was approximately 560 kg/ha, which agrees to what Bucagu et al. (2013) found.

Modelled yields showed the opposite trend, with modelled TP yields being lower than the RF modelled yields. This result agrees with the model functioning, as TP were modelled on basis of only the N added with fixation, the urea and the soil indigenous supply, while RF were modelled with the indigenous supply and often a larger amount of N, P and K than TP. TP receive lower inputs and especially no K, whereas farmers cover the K limitation in RF by applying organic inputs. The focus on N in the TP does not seem to fit the actual needs of the crop or explain the pattern in the observed yields.

The Tephrosia effect is not expressed in the soil fertility either, as shown by the soil analyses before and after the establishment of the experiment. Only pH and SOC are found higher with the TM treatment, however, they are most likely attributed to measurement error. In particular, the method of determining pH in water is sensitive to the timing of sampling, as it positively relates to the level of moisture in the soil (de Vries and Dechering, 1960; Wuest, 2015). The increase in SOC should probably also be attributed to measurement error, as the result of the value of the control sample was almost 50% higher in the second analysis.

Tephrosia intercropping does not always result in yield increase, but on fields that on average showed lower yields, whereas on farms that achieved higher yields, the intercropping positive effect was not apparent. This could relate to the inherent nutrient fertility of each farm. In particular, if N was the most limiting nutrient, Tephrosia should have a positive effect, while in cases that K or P are limiting, the intercropping does not offer an advantage. Also, the amounts of inputs applied per farm differ, as in the RM they depend on what materials are available to the farmers at the specific moment, while in the TM the shrub growth varies per field. This is due to the fact that Tephrosia has its own nutritional and climatic requirements that need to be satisfied for sufficient growth (Kwesiga et al., 2003; Rutunga et al., 2008). In poor soils that present nutrient deficiencies, the growth of the legume can be insufficient, thus reducing the expected benefits (Bucagu et al., 2013).

Despite the K limitation, yields can still increase while the non-limiting nutrients are taken up until the point of accumulation (Janssen et al., 1990). In the calibration of the model, it was hypothesized that a K-efficient cultivar is grown in the study region, which would allow for sufficient yields even in low levels of the nutrient, when others are available. Thus, the N added with the legume mulch and the urea fertilizer might still be needed by the tree.

The use of K as an indicator of predicting yields has also been questioned by Njoroge et al. (2017), who observed large variability in maize yield response, particularly in low K concentrations (< 2 mmol/kg).

Also, Tephrosia plots might have received additional nutrients from the mulch applied in June 2016 as the shrub was planted in October by scrapping off existing mulch. If rains had started, the decomposition of the mulch could have led to a flush of nutrient release which could have been taken up by the tree (Drechsel et al., 1996). Later, in March 2016, the Tephrosia mulch was applied, offering further inputs for the crop. Additionally, all trees in these plots received the recommended amounts of urea fertilizer, while according to the regular management, fertilizer is never enough for all fields or trees.

Concluding, an apparent disagreement of the model with the observations provokes further questioning of SAFERNAC's performance and the understanding of the response to applied nutrients in coffee systems. Perhaps another factor, not considered in the model is determining yields, for example other indirect effects of the intercropping, or other sources of K i.e. the subsoil.

Comparing common nutrient management options and making recommendations

Common farmers' practices or blanket recommendations, including legume intercropping, were not always effective and they should be optimised. In particular, the following conclusions can be drawn:

If the most limiting nutrient is not added at sufficient quantities, yields barely respond.

By construction, the modelled yield response to nutrient additions slows down and eventually reaches a plateau when another nutrient becomes limiting (Janssen et al., 1990). This is the case with urea and Tephrosia applications; N accumulation in the crop and yield might increase, but after a maximum value the yield will not follow, because in the particular soils, K is the limiting factor. Hence, effectiveness of any nutrient source that does not contain K is limited, irrespective of its popularity, apparent usefulness, easiness in application or other reasons supported by extentionists or the farmers themselves. Resolving deficiencies of P, K or other macro- and micro-nutrients has been shown to improve N efficiency (Mafongoya et al., 2006).

If all nutrients are added, it should be done in balanced proportions.

If nutrients are not added in the correct ratios, one of them will become limiting sooner that the rest, resulting in the situation described before. The excessive amounts of the non-limiting nutrients will be wasted. In unbalanced situations, the Agronomic Use Efficiency (AE) of the fertilizer or mulch can easily reach very low levels, even though the AE per nutrient will he higher or lower according to whether it is in shortage or in surplus respectively.

If all nutrients are added, but not at the correct quantities, yields won't increase sufficiently.

Farmers often apply on the coffee fields more nutrients than required, as shown in the average regular management and *Pennisetum sp.* scenario. Application of excessive amounts of nutrients may increase yields, but in an inefficient way. Of course, mulch is often applied for reasons other than simple fertilisation, like soil and moisture conservation, weed reduction and others. However, such use can have important implications for the socio-economic sustainability of smallholder systems as for example farmers often use crop residues from other fields stealing in this way their fertility, but also for environmental reasons.

These conclusions have been demonstrated in many fertilizer trials with various crops when the application of one nutrient resulted in sub-optimal yields, while consequent addition of a limiting nutrient triggered a higher yield response. In maize for example, addition of 20 kg extra P resulted in 40% higher yield than Tephrosia mulch alone (Rutunga et al., 2008). Mukuralinda et al. (2010) also showed that when only N and K was added in P limited soils, yields did not respond and a negative P equilibrium was calculated. Further addition of NPK or mulch led to 3 - 4 times higher yields. For coffee, publications on fertilizer experiments are not so common, particularly when it comes to other nutrients than N. For example, Stephens (1967) recorded response to N fertilizer, after they identified it as the most required nutrient by coffee trees in Uganda. Bucagu et al. (2013) found increase in coffee yield with Tephrosia mulch application, as mentioned earlier, but when combined with NPK yields, improved by an additional 300 - 700 kg/ha. They also calculated the AE of Tephrosia and found it lower than that of farmers' mulch. They attributed this to incomplete decomposition by the end of the season. However, since they experimented on poor soils, another explanation could be that a more balanced mix of nutrients was added with the farmers' mulch. In particular, farmers' mulch contained less N and more K than the Tephrosia mulch. Finally, Baijukya et al. (2005) showed that increasing Tephrosia application rates led to continuous yield improvements. Thus, insufficient mulch amounts result in sub-optimal yields.

All the above publications are based on field trials. The model offers an easier and cheaper approach to diagnose the system requirements and translate them into a concrete fertilization plan. It helps avoid unnecessary treatments that cost money and time but are not reflected in sufficient yield improvement and it can be used to calculate the trade-off between investing on fertilizer and gaining income from the product sale (Maro et al., 2014a).

Similar conclusions were drawn from the analysis of making fertilizer recommendations through simulating fertilizer trials. For the studied farms, it was shown that addition of only K at a rate of 300 kg/ha will allow 14 of the 30 farms to achieve the target yield. Nevertheless, it was shown that site-specific recommendations are necessary as the inherent soil fertility varies per farm.

The required amounts of N and K resemble the farmers' common management. In reality, most farms apply K at least equal to the calculated amount to achieve the target yield (300 kg/ha), but they only acquire suboptimal yields. They also apply sufficient N, 229 kg/ha on average. For 50% of the farms, this is enough to reach the goal. But for the other half farms, the average P inputs are 32 kg/ha, which is extremely low in comparison to what is necessary (300 - 450 kg/ha) according to the model. As this amount is large, another reason to question the model functioning and its usefulness in giving advice arises. The requirements for P based on the model are so high because its recovery fraction is only 0.1. Also, due to the calibration on K limited soils with plenty of N inputs, the improved model might be underestimating SP. This additionally reveals that even when requirements for the most limiting nutrient are covered, another one becomes the problem.

In addition, these calculations of required inputs disagree with the suggested management of urea application. The blanket recommendations that include NPK (particularly 17-17-17) seem to be slightly better targeted, but not precise enough. Either way, the necessity for site-specific and custom-made suggestions is apparent, due to the unique combination of indigenous soil fertility and access to inputs per farm. The same suggestion is given by Vanlauwe and Giller (2006), according to whom, fertilizer recommendations have been designed with limited, outdated data that do not relate with common farmers' practices. The model offers the advantage of site-specific advice, which is particularly important if we consider the large variation in soil fertility that can exist within the same farm (Tittonell et al., 2006).

Eventually, nutrient recommendations should be translated into a combination of inorganic and organic materials. Both sources should be used (Mafongoya et al., 2006) to ensure balanced nutrition with a complementary focus on soil physical and biological fertility. Finally, such advice should be assessed in economic terms as well, as both organic inputs and fertilizers can be hard to find and unaffordable in Africa (Vanlauwe and Giller, 2006). Even if farmers do not have access to optimal resources, this analysis can still be useful to compare available materials and to determine quantities for efficient use.

On the other side, the benefits of using the model are useless if it is incorrectly calibrated. While main trends and great insights on the relative availability of nutrients and their effect on yield can be shown from this study, the question remains, to what extent is the model and its calibration correct. More research on comparing observations with model predictions is necessary, to ensure its correct functioning before any responsible advice can be given or before the conclusions on the blanket recommendations can be drawn.

Conclusions

The main conclusions that can be drawn from this study that aimed to assess the predictive ability of the SAFERNAC model performance and to explore nutrient management options are:

- The model is found unable to accurately predict coffee yields and give fertilizer recommendations in Rwandan farmers' fields.
- The main difference between the region of the model development and the Rwandan fields where it was tested was the low soil K levels on most of the fields.
- The calibration of the model allowed the adaptation of the conditions where it can be applied, however, it did not improve its performance.
- Farmers often use mulch at ineffective quantities depending on their access to resources.
- Intercropping with Tephrosia increases yields in most farms, but not in fields where yields are the highest.
- Even though Tephrosia intercropping does not address the K limitations in the soil, on average it improves yields, indicating the existence of mechanisms that are not known and not considered in the model.
- Blanket recommendations and common nutrient management by farmers might not be effective or efficient.
- If the most limiting nutrient is not provided, yields will not sufficiently respond resulting in inefficiency and waste.
- Improving access to nutrient sources is not enough without adjusting their use to required optimal nutrient proportions and material quality.
- Nutrient inputs can cover inherent soil limitations, but site specific advice on nutrient management is required, due to the variability in the nutrient limitations and the inherent nutrient supply of the soil.
- If it is correctly calibrated, the model can offer an easy and cheap alternative to costly trials.

Suggestions for future research

More research is required to identify whether the model's performance could be improved. To this end, good quality data is a critical factor, thus collection methods that minimize measurement error should be applied. Field trials with inorganic fertilizers, like it was done during the development of SAFERNAC and the multiple calibrations of QUEFTS (Nyombi et al., 2010; Sattari et al., 2014; Smaling and Janssen, 1993), preferably in a factorial design (Sattari et al., 2014), could assist to minimize the errors entailed in the data collection through recall, the uncertainties of the mass fraction values, but also the complex processes from decomposition and nutrient release and the synchronisation with crop needs. Only after the model has shown robustness, should it be tested in farmers' fields. Additionally, larger datasets should be used, to increase the statistical power of the analysis and the chances to capture sufficient variability, which is what desired by a model.

Eventually, data on nutrient uptake by coffee trees and quantification of the harvest index, that would allow more accurate estimation of the physiological efficiencies should also be acquired with analysis of plant samples. As there are many improved cultivars that are progressively replacing old ones, the renewal of such data, which are currently outdated, is necessary.

As trials and plant analysis entail high costs, sharing of datasets among researchers would be a supporting solution.

Finally, if efforts of model calibration with good data prove fruitless, an adaptation of the model to the perennial nature of coffee should be considered.

Reference List

Azeez, J.O., Inyang, U.U., Olubuse, O.C., 2013. Determination of Appropriate Soil Test Extractant for Available Phosphorus in Southwestern Nigerian Soils. Commun. Soil Sci. Plant Anal. 44, 1540–1556. doi:10.1080/00103624.2013.768259

Baijukya, F.P., De Ridder, N., Giller, K.E., 2005. Managing legume cover crops and their residues to enhance productivity of degraded soils in the humid tropics: A case study in Bukoba District, Tanzania. Nutr. Cycl. Agroecosystems 73, 75–87. doi:10.1007/s10705-005-7262-0

Beaumont, H., Fukunaga, E.T., 1958. Factors Affecting the Growth and Yield of Coffee in Kona , Hawaii. Hawaii Agricultural Experiment Station. Available at: https://www.ctahr.hawaii.edu/oc/freepubs/pdf/B-113.pdf (accessed 10.10.1017)

Beegle, K., Carletto, C., Himelein, K., 2012. Reliability of recall in agricultural data. J. Dev. Econ. 98, 34–41. doi:10.1016/j.jdeveco.2011.09.005

Berg, B.B., McClaugherty, C., 2008. Plant Litter: Decomposition, Humus Formation, Carbon Sequestration, Second. ed. Berlin-Heidelberg.

Bokhtiar, S.M., Paul, G.C., Alam, K.M., 2008. Effects of Organic and Inorganic Fertilizer on Growth , Yield , and Juice Quality and Residual Effects on Ratoon Crops of Sugarcane. J. Plant Nutr. 31, 1832–1843. doi:10.1080/01904160802325545

Bote, A.D., 2016. Examining growth, yield and bean quality of Ethiopian coffee trees: towards optimizing resources and tree management. doi:10.18174/383671

Bucagu, C., Vanlauwe, B., Giller, K., 2013. Managing Tephrosia mulch and fertilizer to enhance coffee productivity on smallholder farms in the Eastern African Highlands. Eur. J. Agron. 48, 19–29. doi:10.1016/j.eja.2013.02.005

Cannell, M.G.R., 1985. Dry matter partitioning in tree crops, in: Attributes of Trees as Crop Plants. Institute of Terrestrial Ecology, Abbots Ripton, pp. 160–193.

Cannell, M.G.R., Kimeu, B.S., 1971. Uptake and distribution of macro-nutrients in trees of Coffea arabica. Ann. appl. Biol. 68, 213–230.

Carr, S.J., 1993. Improving cash crops in Africa. Factors influencing the productivity of cotton, coffee, and tea grown by smallholders., World Bank Technical Paper. doi:10.1017/S0014479700024856

Chilombo, G., Yerokun, O., Phiri, M., 2013. Application of various phosphorus extractants on Zambian soils, in: African Crop Science Conference Proceedings. pp. 799–802.

Cooper, J.E., Scherer, H.W., 2012. Nitrogen Fixation, in: Marschner's Mineral Nutrition of Higher Plants. Elsevier Ltd, pp. 389–408. doi:10.1016/B978-0-12-384905-2.00016-9

Couteaux, M.M., Bottner, P., Berg, B., 1995. Litter Decomposition, Climate and Litter Quality. Trends Ecol. Evol. 10, 63–66. doi:10.1016/s0169-5347(00)88978-8

DaMatta, F.M., Ronchi, C.P., Maestri, M., Barros, R.S., 2007. Ecophysiology of coffee growth and production. Brazilian J. Plant Physiol. 19, 485–510. doi:10.1590/S1677-04202007000400014

Das, D.K., Maiti, D., Pathak, H., 2009. Site-specific nutrient management in rice in Eastern India using a modeling approach. Nutr. Cycl. Agroecosystems 83, 85–94. doi:10.1007/s10705-008-9202-2

de Vries, O., Dechering, F.J.A., 1960. Grondonderzoek, 4th ed. Bedrijfslaboratorium voor Grond- en Gewasonderzoek Mariendaal-Oosterbeek, Meppel.

Dourado-Neto, D., Teruel, D. a., Reichardt, K., Nielsen, D.R., Frizzone, J. a., Bacchi, O.O.S., 1998. Principles of crop modelling and simulation: II. the implications of the objective in model development. Sci. Agric. 55, 51–57. doi:10.1590/S0103-90161998000500009

Drechsel, P., Reck, B., 1997. Composted shrub-prunings and other organic manures for smallholder farming systems in southern Rwanda. Agrofor. Syst. 39, 1–12. doi:10.1023/A:1005936723462

Drechsel, P., Steiner, K.G., Hagedorn, F., 1996. A review on the potential of improved fallows and green manure in Rwanda. Agrofor. Syst. 33, 109–136. doi:10.1007/BF00213645

Elrashidi, M., 2010. Selection of an appropriate phosphorus test for soils, USDA NRCS, Lincoln, NE. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051918.pdf (accessed 10.10.1017)

Engels, C., Kirkby, E., White, P., 2011. Mineral Nutrition, Yield and Source-Sink Relationships, Marschner's Mineral Nutrition of Higher Plants: Third Edition. Elsevier Ltd. doi:10.1016/B978-0-12-384905-2.00005-4

Ezui, K.S., Franke, A.C., Mando, A., Ahiabor, B.D.K., Tetteh, F.M., Sogbedji, J., Janssen, B.H., Giller, K.E., 2016. Fertiliser requirements for balanced nutrition of cassava across eight locations in West Africa. F. Crop. Res. 185, 69–78. doi:10.1016/j.fcr.2015.10.005

FAO, 2016. FAO Country Profiles - Rwanda [WWW Document]. URL http://www.fao.org/rwanda/en/ (accessed

9.22.16).
FAOSTAT, 2016. Coffee production per country [WWW Document]. URL http://faostat3.fao.org/browse/Q/*/E
Fermont, A., Benson, T., 2011. Estimating yield of food crops grown by smallholder farmers: A Review in the Uganda Context. IFPRI Discuss. Pap. 01097 1–57.
Ferreras, L., Gomez, E., Toresani, S., Firpo, I., Rotondo, R., 2005. Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. Bioresour. Technol. 97, 635–640. doi:10.1016/j.biortech.2005.03.018
Field, A.P., Miles, J., Field, Z., 2012. Discovering statistics using R. Sage Publications Ltd, London.
Flores, R.A., Urquiaga, S., Alves, B.J.R., Collier, L.S., Boddey, R.M., 2012. Yield and Quality of Elephant Grass Biomass Produced in the Cerrados Region for Bioenergy. Eng. Agríc. Jaboticabal 32, 831–839. doi:10.1590/S0100-69162012000500003
Fowler, S.M., Watson, C.A., Wilman, D., 1993. N, P And K On Organic Farms - Herbage And Cereal Production, Purchases And Sales. J. Agric. Sci. 120, 353–360. doi:10.1017/S0021859600076516
Giller, K., 1993. Nitrogen fixation in tropical cropping systems. 2nd ed. Field Crops Research. CABI Publishing. doi:10.1016/0378-4290(93)90012-C. ISBN 0-85199-417-2
Harris, F., 2002. Management of Manure in Farming Systems in Semi-Arid West Africa. Exp. Agric. 38. doi:10.1017/S0014479702000212
Henao, J., Baanante, C., 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa, Africa. Alabama.
IFDC, 2014. Rwanda Fertilizer Assessment. International Fertilizer Development Center. Alabama. Available at: https://ifdcorg.files.wordpress.com/2016/05/rwanda-fertilizer-assessment.pdf (accessed 10.10.2017)
International Coffee Organization, 2016a. The Current State of the Global Coffee Trade [WWW Document]. URL http://www.ico.org/monthly_coffee_trade_stats.asp (accessed 10.20.16).
International Coffee Organization, 2016b. Rwanda - Infogram [WWW Document]. URL https://infogr.am/_/GnrW2Lpn42ZuUWGkkQR6 (accessed 10.17.17).
IUSS Working Group WRB, 2014. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps, World Soil Resources Reports No. 106. doi:10.1017/S0014479706394902
Jama, B.A., Nair, P.K.., 1996. Decomposition and nitrogen-mineralization patterns of of Leucaena leucocephala and Cassia siamea mulch under tropical semiarid conditions in Kenya. Plant Soil 275–285. doi:10.1007/BF00009338
Janssen, B.H., 2011a. Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. I. New soil organic matter and residual effect of P from fertilizers and farmyard manure in Kabete, Kenya. Plant Soil 339, 3–16. doi:10.1007/s11104-010-0587-8
Janssen, B.H., 2011b. Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. II. Crop nutrient equivalents, balanced supplies of available nutrients, and NPK triangles. Plant Soil 339, 17–33. doi:10.1007/s11104-010-0590-0
Janssen, B.H., 2004. Report on an advisory mission on Crop Nutrition to Tanzanian Coffee Research Institute (TaCRI). Lyamungu (Moshi).
Janssen, B.H., 1998. Efficient use of nutrients: An art of balancing. F. Crop. Res. 56, 197–201. doi:10.1016/S0378-4290(97)00130-5
Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J., van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46, 299–318. doi:10.1016/0016-7061(90)90021-Z
Jassogne, L., Nibasumba, A., Wairegi, L., Baret, P.V., Deraeck, J., Mukasa, D., Wanyama, I., Bongers, G., Asten, P.J.A. van, Jassogne, 2013. Coffee/Banana Intercropping as an Opportunity for Smallholder Coffee Farmers in Uganda, Rwanda and Burundi., in: Blomme, G., Asten, P. van, Vanlauwe, B. (Bernard) (Eds.), Banana Systems in the Humid Highlands of Sub-Saharan Africa. Enhancing Resilience and Productivity. Croydon, pp. 144–159. doi:10.1080/14735903.2012.714576
Kanté, S., Smaling, E.M.A., Keulen, H. Van, 2007. Nutrient balances for different farm types in Southern Mali. Geo-Information Sci. 557–566.
Kwesiga, F., Akinnifesi, F.K., Mafongoya, P.L., McDermott, M.H., Agumya, A., 2003. Agroforestry research and development in southern Africa during the 1990s: Review and challenges ahead. Agrofor. Syst. 59, 173–186. doi:10.1023/B:AGFO.0000005222.68054.38
Lehmann, J., 2003. Subsoil root activity in tree-based cropping systems. Plant Soil 255, 319–331. doi:10.1023/A:1026195527076
Lekasi, J.K., Bekunda, M.A., Woomer, P.L., Tenywa, J.S., Lekasp, J.K., Bekunda1, M.A., Tenywa, J., 1999.

Decomposition of Crop Residues in Banana-Based Cropping Systems of Uganda. Biol. Agric. Hortic. Biol. Agric. Hortic. 171, 1–10. doi:10.1080/01448765.1999.9754819

Lima, D.M., Lindomar, D.S.M., Marcelo, A.T., Jose, F.T.D.A., 2015. The nutritional efficiency of Coffea spp. A review. African J. Biotechnol. 14, 728–734. doi:10.5897/AJB2014.14254

Liu, M., Yu, Z., Liu, Y., Konijn, N.T., 2006. Fertilizer requirements for wheat and maize in China: The QUEFTS approach. Nutr. Cycl. Agroecosystems 74, 245–258. doi:10.1007/s10705-006-9002-5

Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contam. Hydrol. 7, 51–73. doi:10.1016/0169-7722(91)90038-3

Loveridge, S., Mpyisi, E., Emmanuel, S., 2002. Rwandan Smallholder Coffee Tree Maintenance and Cherry Processing Techniques. Rwanda Ministry of Agriculture, Livestock and Forestry. Kigali. Available at: http://fsg.afre.msu.edu/rwanda/coffee_maint_processing.pdf (accessed 12/10.2017)

Mafongoya, P.L.L., Bationo, A., Kihara, J., Waswa, B.S., Mafongoya, P.L.L., Bationo, A., Kihara, J., Waswa, B.S., Mafongi, P.L., Bationo, A., Kihara, J., Waswa, B.S., 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutr. Cycl. Agroecosystems 76, 137–151. doi:10.1007/s10705-006-9049-3

Mallarino, A.P., 1995. Comparison of Mehlich, Olsen and Bray. North Cent. Extension-Industry Soil Fertil. Conf. 11, 96–102.

Malunda, D., 2012. Report for the African Centre for Economic Transformation (ACET) Rwanda: Case Study on Economic Transformation. Inst. Policy Anal. Res. – Rwanda 1–64.

Maro, G., Janssen, B., Msanya, B., Mrema, J., 2014. Economic Optimization of Nutrient Application to Coffee in Northern Tanzania Using SAFERNAC. Int. J. Plant Soil Sci 3, 1096–1111.

Maro, Mrema, J., Msanya, B., Janssen, B., Teri, J., 2014a. Developing a Coffee Yield Prediction and Integrated Soil Fertility Management Recommendation Model for Northern Tanzania. Int. J. Plant Soil Sci. 3, 380–396.

Maro, Msanya, B., Mrema, J., 2014b. Soil Fertility Evaluation for Coffee (Coffea arabica) in Hai and Lushoto Districts , Northern Tanzania. Int. J. Plant Soil Sci. 3, 934–947.

Marschner, P., Rengel, Z., 2011. Nutrient Availability in Soils, Marschner's Mineral Nutrition of Higher Plants: Third Edition. Elsevier Ltd. doi:10.1016/B978-0-12-384905-2.00012-1

Mayer, D.G., Butler, D.G., 1993. Statistical validation. Ecol. Modell. 68, 21–32. doi:10.1016/0304-3800(93)90105-2

Motsara, M.R., Roy, R.N., 2008. Guide to laboratory establishment for plant nutrient analysis, FAO Fertilizer and Plant Nutrition Bulletin 19. Rome.

Mukuralinda, A., Tenywa, J.S., Verchot, L., Obua, J., Nabahungu, N.L., Chianu, J.N., 2010. Phosphorus uptake and maize response to organic and inorganic fertilizer inputs in Rubona, Southern Province of Rwanda. Agrofor. Syst. 80, 211–221. doi:10.1007/s10457-010-9324-9

Nair, K.P.P., 2010. Coffee. Agron. Econ. Important Tree Crop. Dev. World 181–208. doi:10.1016/B978-0-12-384677-8.00006-0

Ng, S.K., Iyer, G.C., Ratnasingam, K., Buloh, S., 1974. Laboratory Errors of Soil Analysis. J. Rubb. Res. Inst. Malaysia 24, 39–44.

Nijhof, K., 1987. The Concentration of Macro-Nutrients in Plant Parts of Tropical Perennials. Available at PPS: office.pp@wur.nl

Njoroge, J.M., 1985. Effects of Nitrogen Rates and Frequency of Application on Coffee Yield and Quality in Kenya. Acta Hortic. 158, 283–291.

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. F. Crop. Res. 214, 321–330. doi:10.1016/j.fcr.2017.09.026

Norman, M.J.T., 1963. The pattern of dry matter and nutrient content changes in native pastures at Katherine, N.T. 86. Available at: http://www.publish.csiro.au/ea/pdf/ea9630119 (accessed 12.10.2017)

Nyombi, K., van Asten, P.J.A., Corbeels, M., Taulya, G., Leffelaar, P.A., Giller, K.E., 2010. Mineral fertilizer response and nutrient use efficiencies of East African highland banana (Musa spp., AAA-EAHB, cv. Kisansa). F. Crop. Res. 117, 38–50. doi:10.1016/j.fcr.2010.01.011

Nzeyimana, I., Hartemink, A.E., de Graaff, J., 2013. Coffee farming and soil management in Rwanda. Outlook Agric. 42, 47–52. doi:10.5367/oa.2013.0118

Nzeyimana, I., Hartemink, A.E., Ritsema, C., Stroosnijder, L., Lwanga, E.H., Geissen, V., 2017. Mulching as a strategy to improve soil properties and reduce soil erodibility in coffee farming systems of Rwanda. Catena 149, 43–51. doi:10.1016/j.catena.2016.08.034

Orozco, F.H., Cegarra, J., Trujillo, L.M., Roig, A., 1996. Vermicomposting of coffee pulp using the earthworm Eisenia fetida: Effects on C and N contents and the availability of nutrients. Biol. Fertil. Soils 22, 162–166. doi:10.1007/s003740050092

Paliwal, K., Manoharan, K., 1987. Nutrient Budget of Themeda Triandra and Heteropogon Contortus Dominated Grasslands of Tamil Nadu in South India . Available at: http://internationalgrasslands.org/files/igc/publications/1997/1-10-109.pdf. (accessed 10.10.2017)
Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: Application of an organic resource database. Agric. Ecosyst. Environ. 83, 27–42. doi:10.1016/S0167-8809(00)00267-X
Pierzynski, G.M., 2000. Methods of Phosphorus Analysis for Soils , Sediments , Residuals , and Waters. South. Coop. Ser. Bull. 408, 131. doi:citeulike-article-id:7529961
R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Comp uting. Vienna. url: https://www.R-project.org/
Reitermanová, Z., 2010. Data Splitting. WDS'10 Proceedings of Contributed Papers, Part I, 31–36 31–36.
Rose, T., Bowden, B., 2013. Matching Soil Nutrient Supply and Crop Demand during the Growing Season. Improv. Water Nutr. Effic. Food Prod. Syst. 93–103. doi:10.1002/9781118517994.ch6
Rufino, M.C., Tittonell, P., van Wijk, M.T., Castellanos-Navarrete, A., Delve, R.J., de Ridder, N., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest. Sci. 112, 273–287. doi:10.1016/j.livsci.2007.09.011
Rutunga, V., Karanja, N.K., Gachene, C.K.K., 2008. Six month-duration Tephrosia vogelii Hook.f. and Tithonia diversifolia (Hemsl.) A.Gray planted-fallows for improving maize production in Kenya. Biotechnol. Agron. Soc. Environ. 12, 267–278.
RVO, 2017. Diergebonden forfaitaire gehalten. Available at: https://www.rvo.nl/file/tabel-4-diergebonden-forfaitaire-gehalten-2017 (accessed 10.10.2017)
Sanginga, N. and Woomer, P.L. (eds.). 2009. Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture. Nairobi. 263 pp.
Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L., Janssen, B.H., 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. F. Crop. Res. 157, 35–46. doi:10.1016/j.fcr.2013.12.005
Schick, B.J., Kratz, S., Rückamp, D., Shwiekh, R., Haneklaus, S., 2013. Comparison and Inter-Calibration of Different Soil P Tests Used in the Baltic Sea Countries. Baltic Forum for Innovative Technologies for Sustainable Manure Management. Available at: http://www.balticmanure.eu/download/Reports/method_calibration_final_web.pdf (accessed 10.10.2017)
Schut, A.G.T., n.d. Lecture Notes, Models for Ecological Systems.
Smaling, E.M.A., Janssen, B.H., 1993. Calibration of quefts, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59, 21–44. doi:10.1016/0016-7061(93)90060-X
Smaling, E.M.A., Stoorvogel, J.J., Windmeijer, P.N., 1993. Calculating soil nutrient balances in Africa at difference scales, II. Distict scale. Fertil. Res. 35, 237–250. doi:10.1007/BF00750642
Stephens, B.Y.D., 1967. Experiments with Nitrogen and Magnesium Fertilizers on Coffee in Uganda. Exp. Agric. 191–203.
Tittonell, P., Leffelaar, P.A., Vanlauwe, B., van Wijk, M.T., Giller, K.E., 2006. Exploring diversity of crop and soil management within smallholder African farms: A dynamic model for simulation of N balances and use efficiencies at field scale. Agric. Syst. 91, 71–101. doi:10.1016/j.agsy.2006.01.010
Tittonell, P., Rufino, M.C., Janssen, B.H., Giller, K.E., 2010. Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems-evidence from Kenya. Plant Soil 328, 253–269. doi:10.1007/s11104-009-0107-x
Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric. Ecosyst. Environ. 110, 166–184. doi:10.1016/j.agee.2005.04.003
Unknown, 2013. Coffee - Rwanda: Lower prices could lead farmers to other crops. Africa Res. Bull. Econ. Financ. Tech. Ser. 50, 19960B–19961B. doi:10.1111/j.1467-6346.2013.05148.x
Unknown, 2010. Coffee: Rwanda. Output is expected to climb significantly in 2010. Africa Res. Bull. Econ. Financ. Tech. Ser. 46, 18533–18534. doi:10.1111/j.1467-6346.2010.03044.x
Unknown, 2006. Coffee: Rwanda Beans for speciality brews have become a top priority. Africa Res. Bull. Econ. Financ. Tech. Ser. 43, 17090B–17090C. doi:10.1111/j.1467-6346.2006.00468.x
van der Vossen, H., 2005. A Critical Analysis of the Agronomic and Economic Sustainability of Organic Coffee Production. Expl. Agric. 41, 449–473. doi:10.1017/S0014479705002863

van Ittersum, M.K., Rabbinge, R., 1997. Concept of production ecology for analysis and quantification of agricultural imput-output combination. F. Crop. Res. 52, 197–208.
Vanlauwe, B., Diels, J., Sanginga, N., Merckx, R., 2002. Integrated plant nutrient management in sub-Saharan Africa: from concept to practice. CABI Publishing, London.
Vanlauwe, B., Giller, K.E., 2006. Popular myths around soil fertility management in sub-Saharan Africa. Agric. Ecosyst. Environ. 116, 34–46. doi:10.1016/j.agee.2006.03.016
Vanlauwe, B., Zingore, S., 2010. Integrated Soil Fertility Management: An operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24.
Verdoodt, A., Ranst, E. Van, 2003. Land evaluation for agricultural production in the tropics. A large-scale land suitability classification for Rwanda. Laboratory of Soil Science, Ghent University, Gent. Available at: https://biblio.ugent.be/publication/212638 (accessed 10.10.2017)
Wallach, D., Makowski, D., Jones, J.W., Brun, F., 2014. Model Evaluation, Working with Dynamic Crop Models. doi:10.1016/B978-0-12-397008-4.00009-5
Wang, N., Jassogne, L., van Asten, P.J.A., Mukasa, D., Wanyama, I., Kagezi, G., Giller, K.E., 2015. Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. Eur. J. Agron. 63, 1–11. doi:10.1016/j.eja.2014.11.003
Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., O'Donnell, J., Rowe, C.M., 1985. Statistics for the evaluation and comparison of models. J. Geophys. Res. Ocean. 90, 8995–9005. doi:10.1029/JC090iC05p08995
Witt, C., Dobermann, A., Abdulrachman, S., Gines, H.C., Guanghuo, W., Nagarajan, R., Satawatananont, S., Thuc Son, T., Sy Tan, P., Van Tiem, L., Simbahan, G.C., Olk, D.C., 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. F. Crop. Res. 63, 113–138. doi:10.1016/S0378-4290(99)00031-3
Wolf, A.M., Baker, D.E., 1985. Comparisons of soil test phosphorus by Olsen, Bray P1, Mehlich I and Mehlich III methods [1]. Commun. Soil Sci. Plant Anal. 16, 467–484. doi:10.1080/00103628509367620
Wrigley, G., 1988. Coffee, First. ed. Longman Singapore Publishers (Pte) Ltd., New York.
Wuest, S.B., 2015. Seasonal Variation in Soil Bulk Density, Organic Nitrogen, Available Phosphorus, and pH. Soil Sci. Soc. Am. J. 79, 1188. doi:10.2136/sssaj2015.02.0066

Appendices

Appendix 1: Good coffee management practices

Good farming practices for coffee tree maintenance are important to achieve good yields and high quality coffee beans.

Soil nutrient management, either with the use of artificial fertilizers or organic inputs, like mulch, are essential for balanced crop nutrition. Mulch in coffee should be applied from the transplanting of the seedlings onwards and throughout the productive life of the tree (Nair, 2010).

Weeding is necessary and is performed either with herbicides or mechanical control (Nair, 2010).

Pruning of coffee trees is also done and prunings can be left on the soil to act as mulch (Nair, 2010). According to (Loveridge et al., 2002), trimming of trees can be done in two ways: pruning (cut off branches from less productive parts of tree) and "egourmandage" where errant buds and dead branches are removed. The importance of pruning lies on the growth control of the tree, which keeps elongating to heights impractical for harvesting, but also to remove branches that are no longer productive, as plagiotropic nodes of branches produce flowers only once (Wrigley, 1988).

Shading of coffee is also often practiced, as coffee is a shade-loving plant (DaMatta et al., 2007). Various trees can function as shade and windbreaks. For example, *Cordia* spp., *Grevillea robusta*, *Albizia* spp., *Leucaena leucocephala*, and *Cypress* spp. (Nair, 2010). However, coffee can also grow well in full sun and even give higher yields, as long as no nutrient related limitations exist (Bote, 2016). In reality, coffee has adopted as a forest species, under the canopy, so the leaves have relatively low needs in light for photosynthesis. When it is grown in full sun, though, it has the capacity to produce more flowers, berries (yield) provided that sufficient nutrition is available in order for the tree to maintain its long-term health.

Appendix 2: Materials and Methods

Appendix 2.1: The data used in the analysis

Appendix 2.1a: Soil fertility data before the establishment of the experiment

FieldNr	pH	TOC (g/kg)	TN (g/kg)	P-Bray-I (mg/kg)	K-exch (mmol/kg)
1	5.55	8.3	2.50	42.49	0.52
2	5.42	2.0	2.40	14.91	0.75
3	5.77	15.2	2.00	110.53	1.99
4	5.77	10.8	3.15	23.92	2.12
5	5.05	6.5	3.00	20.05	2.07
6	4.94	26.5	0.75	19.18	0.72
7	5.15	18.9	5.25	30.45	1.32
8	5.59	20.4	1.25	59.79	1.50
9	5.59	16.6	3.50	58.67	2.19
10	5.49	15.9	2.75	24.68	1.68
11	5.25	13.5	2.00	33.41	1.98
12	5.32	20.2	2.50	85.50	0.66
13	5.96	19.7	4.25	212.52	4.06
14	5.68	17.2	1.75	107.54	2.41
15	5.66	9.8	0.50	90.88	0.89
16	5.39	0.8	1.50	83.46	0.41
17	5.70	6.4	2.00	83.03	0.30
18	5.17	18.9	3.00	40.98	0.50
19	5.77	11.2	3.50	41.10	1.29
20	5.32	12.7	2.65	92.47	0.72
21	5.54	21.7	2.75	97.85	1.43
22	5.30	20.3	1.75	44.92	0.94
23	5.48	14.7	5.25	72.90	2.10
24	5.45	18.9	2.80	1.36	1.44
25	5.22	13.1	2.75	56.88	1.21
26	6.02	31.7	2.90	126.75	2.02
27	5.93	25.3	5.75	142.33	1.63
28	5.82	21.0	2.00	125.48	1.10
29	5.64	22.8	3.75	46.76	2.66
30	5.09	14.3	1.90	2.27	1.33

Appendix 2.1b: Soil fertility data after the establishment of the experiment (only the average values of the four technicians are shown)

FieldNr	pH	TOC (g/kg)	TN (g/kg)	P-Bray-I (mg/kg)	P-Olsen (mg/kg)	K-exch (mmol/kg)
1	5.34	22.6	2.5	94.29	32.14	1.05
2	5.61	15.8	2.3	75.10	18.15	1.54
3	5.71	27.1	2.8	98.50	69.12	1.55
4	5.55	21	3.1	45.13	26.25	1.53
5	5.51	17.8	3.2	58.68	46.12	0.54
6	5.52	18.9	3.5	60.34	39.24	2.26
7	5.71	20.8	3.0	43.52	9.89	0.64
8	5.19	27.1	1.6	20.72	13.15	0.61
9	6.09	28.6	3.0	128.25	82.90	2.53
10	5.21	19.9	3.0	44.23	24.92	0.72
11	5.13	21.1	4.8	29.50	21.51	0.52
12	5.98	21	3.8	25.43	18.71	2.30
13	5.91	21.3	2.0	149.00	42.81	1.07
14	5.24	21.3	3.3	102.58	85.29	1.16
15	5.91	22.2	0.5	128.60	74.06	2.14
16	5.63	18.2	3.2	44.92	40.13	0.83
17	5.12	8.2	3.1	17.13	15.27	2.20
18	5.52	3.1	0.8	8.81	5.64	0.84
19	5.71	25.4	2.1	70.49	46.63	1.73
20	5.81	18.5	4.0	80.10	65.28	2.30
21	5.62	16.1	2.5	36.20	25.86	2.20
22	6.17	32.5	7.1	161.71	86.96	1.84
23	5.44	19.5	2.7	81.36	71.77	0.77
24	5.32	22	3.1	1.52	1.31	1.61
25	5.94	20.4	4.1	223.17	144.91	3.96
26	5.94	11.2	2.3	86.43	41.26	0.41
27	6.11	35.4	2.8	138.58	64.16	1.91
28	5.82	19.5	1.4	109.80	59.19	1.07
29	5.40	1.1	1.7	74.38	31.04	0.52
30	5.24	19.6	2.5	15.16	3.24	1.51

Appendix 2.1c: Yield data (kg parchment coffee per ha) of years 2012 – 2016 on the Regular Fields (RF) and of 2016 of the Tephrosia Plots (TP)

FieldNr	RF 2012	RF 2012	RF 2014	RF 2015	RF 2016	TP 2016
1	1494	1866	1866	1680	1376	2376
2	3360	3360	2800	3360	1250	1688
3	1568	1344	1344	896	1500	2126
4	1120	1400	1400	1820	2000	2688
5	3112	3734	3422	3734	1000	1594
6	2240	2520	2240	2800	3062	3812
7	3734	4106	4480	3360	2562	3312
8	1866	2016	2240	2054	2376	2844
9	3112	3112	4230	3112	3750	4376
10	2240	2240	1866	2240	2126	2500
11	3054	2546	3054	3054	3750	3876
12	1400	1960	1960	1960	2376	2938
13	1704	1948	1802	1948	3126	3968
14	2800	2240	2240	2520	2438	3062
15	1866	2178	2178	1866	2312	2688
16	3920	3360	3360	2800	2688	2938
17	3360	3136	3136	3360	1688	2250
18	2800	2178	2178	2488	1500	2250
19	1680	1680	1960	2240	4344	3562
20	224	672	672	1344	1468	1594
21	1494	2240	2240	2986	1876	2812
22	1440	1440	1600	1440	1312	2062
23	1120	1344	1344	1494	2376	2406
24	1494	1494	1306	1680	1376	1938
25	2240	2800	2016	2576	3126	3876
26	1568	1792	1568	2240	744	750
27	2464	3136	2956	1344	3688	3662
28	1280	1504	1280	1120	1938	2062
29	1680	1960	2240	1680	2588	2988
30	1494	1494	1866	1606	1376	2000

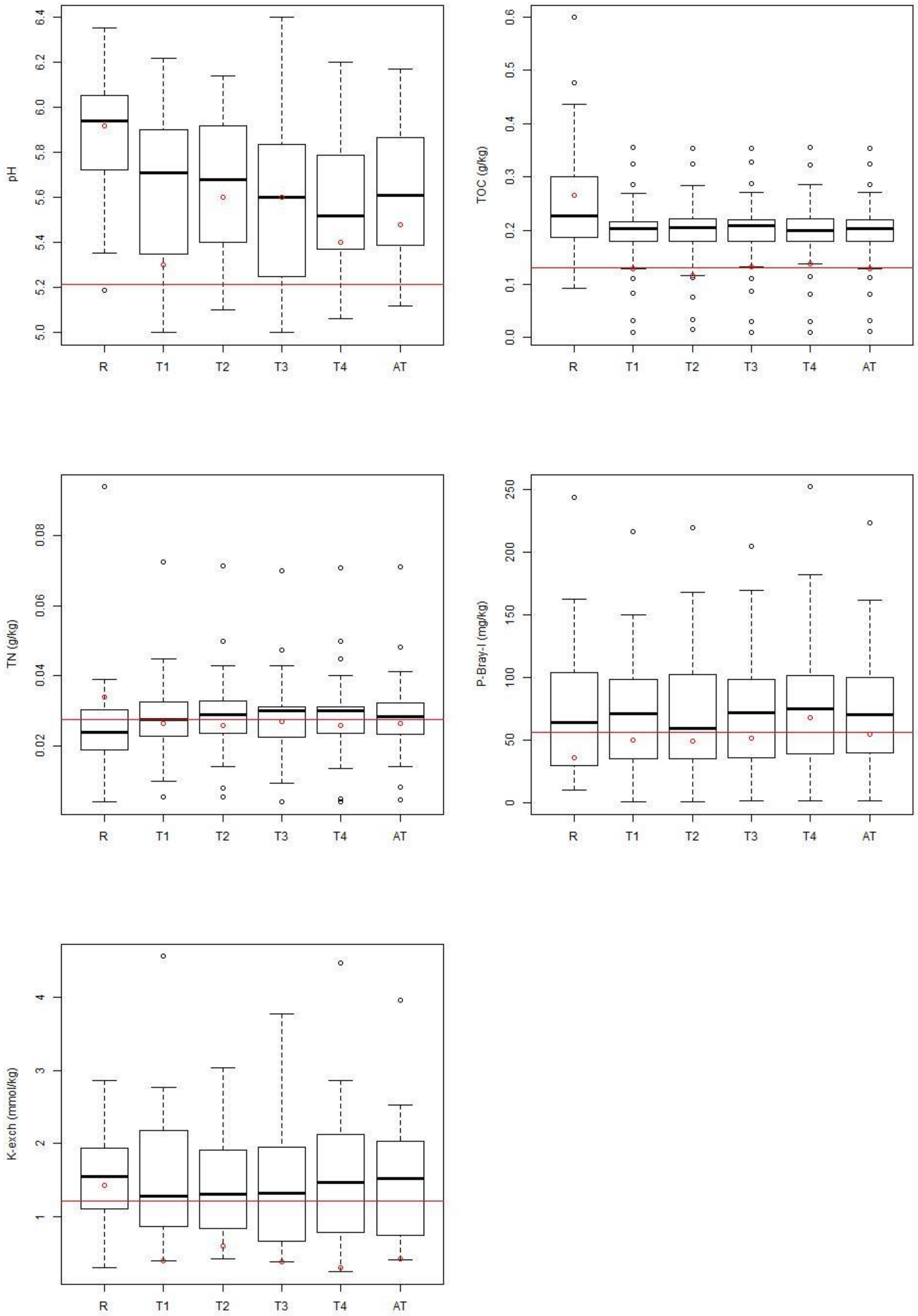
Appendix 2.1d: Quantities of mulch (kg per farm) and of fertilizer (kg per farm) used by the interviewed farmers. P = *Pennisetum sp.* mulch, BR = Bean residues, BN = Banana leaves, MR = Maize residues, TH = *Themeda sp.* mulch, SC = Sugarcane leaves, SB = Soybean residues, CP = Coffee pulp, WOF = Weeds from other fields, C = Compost, LOF = Leftover animal feed, MN = Manure, CM = Compost and manure mix, CMF = Compost, manure and leftover animal feed mix, F = Fertilizer. Plant material is measured in dry weight, coffee pulp, compost and manure are measured in fresh weight

FieldNr	P	BR	BN	MR	TH	SC	SB	CP	WOF	C	LOF	M	CM	CMF	F
1, 2	5940	0	0	0	39600	3960	0	0	0	0	0	1250	0	0	150
3	1200	NA	0	800	0	0	0	0	0	0	0	390	0	0	15
4	405	475	183	1125	NA	0	0	0	0	1000	0	0	0	0	28
5	2700	0	0	754	650	0	0	0	0	900	0	300	0	0	70
6	1800	0	NA	2262	0	0	0	0	0	520	0	0	0	0	16
7	3200	375	150	1800	0	0	30	0	0	yes	0	yes	500	0	15
8	4500	0	0	1800	0	0	0	0	0	yes	0	yes	4850	0	57
9	875	200	40	100	0	0	0	1000	100	yes	0	yes	1200	0	50
10, 16	2400	50	0	0	400	0	0	0	0	750	3000	0	0	0	20
11	21000	250	180	15000	0	0	160	0	0	yes	7800	yes	1500	0	40
12	1750	500	0	1000	0	300	0	0	0	yes	0	yes	1200	0	60
13	1800	1000	0	720	0	0	0	0	0	yes	0	yes	7800	0	50
14	1600	0	500	7000	0	0	0	0	0	yes	0	yes	2000	0	60
15	1500	0	560	330	0	0	0	0	0	0	0	0	0	0	100
17	18360	240	0	432	0	0	144	0	0	200	0	0	0	0	90
18	2000	0	300	0	0	0	0	0	0	0	1825	0	0	0	20
19	9000	0	0	0	0	0	0	0	0	0	0	0	0	0	30
20	25500	0	0	0	0	0	120	0	NA	0	NA	630	0	0	0
21	1000	150	1050	1500	0	0	0	0	0	0	0	0	0	0	10
22	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
23	3000	60	NA	300	0	0	0	0	0	0	0	0	0	0	15
24	2000	140	750	3400	0	0	30	0	450	765	0	0	0	0	25
25	900	150	400	600	0	0	240	0	0	0	4680	0	0	0	20
26	1800	0	0	1600	0	0	0	0	0	yes	yes	yes	0	4000	50
27	600	200	1512	2620	0	0	0	0	0	yes	yes	yes	0	350	10
28	1600	1800	875	5000	0	3000	0	0	0	yes	0	yes	1500	0	198
29	180	90	0	0	0	0	0	0	0	0	0	0	0	0	0
30	NA	10	0	300	0	0	0	0	0	0	300	0	0	0	46

Appendix 2.1e: Quantities of Tephrosia added as mulch (tons dry matter per ha) and soil group of each Tephrosia plot

FieldNr	Tephrosia biomass (t/ha)	Reference Soil Group
1	7.747	Humic Acrisols
2	0.674	Humic Ferralsols
3	1.374	Humic Ferralsols
4	0.720	Humic Ferralsols
5	0.335	Humic Acrisols
6	0.550	Humic Ferralsols
7	0.961	Humic Ferralsols
8	3.395	Humic Alisols
9	0.910	Humic Acrisols
10	1.984	Humic Acrisols
11	2.315	Humic Acrisols
12	1.262	Humic Ferralsols
13	0.740	Humic Ferralsols
14	10.032	Humic Ferralsols
15	3.033	Technosol
16	0.913	Humic Alisols
17	2.847	Humic Acrisols
18	1.044	Humic Ferralsols
19	1.041	Humic Acrisols
20	4.807	Humic Acrisols
21	1.534	Humic Acrisols
22	0.895	Humic Acrisols
23	1.010	Humic Acrisols
24	1.235	Humic Ferralsols
25	4.685	Humic Ferralsols
26	0.907	Dystric Leptosols
27	2.347	Dystric Leptosols
28	1.680	Dystric Leptosols
29	1.374	Humic Alisols
30	0.237	Humic Ferralsols

Appendix 2.2a: Comparison of soil results between technicians (T). Red points indicate the result of the control sample. The red line indicates the results of the control sample in the first analysis



Appendix 2.2b: ANOVA for differences in the soil analysis between the four technicians

Script: anova_variable <- aov(variable ~ technician + Error(FieldNr/technician), data=tech_data)

Variable	Df	Sum of Squares	Mean square	F value	Significance
pH					
Technician	3	0.311	0.10368	4.803	0.004
Residuals	90	1.943	0.02159		
SOC					
Technician	3	0.0046	0.001552	1.278	0.287
Residuals	90	0.1093	0.0001215		
TN					
Technician	3	0.00046	0.0001535	0.421	0.738
Residuals	90	0.03278	0.0003642		
P-Bray-I					
Technician	3	2116	705.5	6.727	0.00038
Residuals	90	9439	104.9		
K-exch					
Technician	3	326	108.8	1.003	0.395
Residuals	90	9762	108.5		

Appendix 2.3: The questionnaire used for the farmers' interviews

Date and time of interview: ______
Name of respondent: ______
Field Number: _______

SECTION I: BACKGROUND AND SOCIO-ECONOMIC DATA

1. Location: Village: ______Cell: _______ Sector: ________ District:_________ Province:______________

2. Sex of respondent: *1. Male* _____ *2. Female:*_______

3. Name of household head (if other than respondent): ____________

4. *Sex of household head: 1. Male _____ 2. Female:_______*

5. What is the annual average income of the household? (*Seek for the consent of the respondent)*

6. What is the most important source of income for your households? ____________
   Possible solutions: Agriculture, Livestock, Agriculture and livestock, Formal employment, Informal employment/small business, Other (specify): _______

7. *What percentage of the household's income comes from selling coffee?* ________________

SECTION II. TREE/COFFEE MANAGEMENT AND MULCH PRACTICE

8. What is the total size of your farm?
   1. Less than 0.6 ha: __________
   2. 0.6 ha – 1.0 ha: ___________
   3. 1.1 ha – 2.0 ha: ___________
   4. Greater than 2.0 ha: ________

9. What are the major types of crops that are grown on the farm?
   1. ________________________ 4. __________________________
   2. ________________________ 5. __________________________
   3. ________________________ 6. __________________________

10. How many coffee fields do you have?

11. (a). How many coffee trees in total do you have? _____________
    (b). How many coffee trees per ha do you have? _______

12. (a). What is the average annual coffee yield (green berries) you get (kg/tree) _____________
    (b). What is the dry coffee yield (no pulp) in kg/tree? _____________

13. (a). Do you dry coffee beans? Yes ____ No: _____
    (b). If yes, what do they do with the pulp? _______________

14. When was your coffee planted? _____________

15. What management practices do you apply on coffee fields and when do you apply each of them?

Practice	Yes/No	Timing
Weeding		
Fertilizing		
Mulching		
Pruning		
Other		

16. Which type and amount of mulch per year (specify amount in kg for each mulch). And which part of the plant do you apply?

Mulch type	Amount	Plant part

17. Where do you get the above mulch from?

Mulch type	Source 1	Source 2

18. (a). Do you mix the mulches or apply separately? ______________
(b). If you apply them separately, how do you distribute them in the fields? ____

19. (a). Is this mulch enough for the whole coffee field(s)? _________
(b). If not, for how much is it enough? _______________

20. (a). Do you sell mulch? Yes ____ 2.No: _____
(b). At what cost per kg or bundle? ________________________________

21. What are the 3 most important purposes of the mulch?
1. ___________________________________
2. ___________________________________
3. ___________________________________

22. What are the 3 best mulch materials and why?
1. ____
2. ____
3. ____

23. If you apply fertilizer, how much do you apply and how often per year?

24. (a). Do you apply compost on coffee? Yes ____ No: _____
(b). If yes, how much and how often? _________

25. What do you do with the prunings of the coffee? _____________________

26. (a). Do you grow other crops together with the coffee trees? Yes ____ No: _____
(b). If you grow crops among your coffee farms, what do you do with the residues? _______________

27. (a). How many of these animals do you have on-farm?
- Cows
- Goats
- Sheep
- Chickens
- Pigs

(b). What do you do with the manure? ______________________________________

28. Are animals allowed to graze in your coffee fields?

Appendix 2.4: Nutrient contents of applied plant materials according to different literature sources and the country where the material was grown, when available. Rows in bold are the values selected for the analysis. ORD = Organic Resource Database (Palm et al., 2001), available at PPS: office.pp@wur.nl

Plant part	Country	N (%)	P (%)	K (%)	Source
Napier grass (*Pennisetum* sp.)					
NA		1.51	0.27	3.51	(Nair, 2010)
NA	Brasil	1.1	0.1	2.8	(Flores et al., 2012)
Leaf	Brasil	2.25	0.13	2.1	(Sanginga and Woomer, 2009)
Leaf	Kenya	**1.97**	**0.14**	**3.85**	**ORD**
Mulch		1.5	0.26	3.5	(van der Vossen, 2005)
Maize (*Zea mais*)					
Stover		2.11	0.15	1.61	(Nair, 2010)
Residue		**0.43**	**0.14**	**1.23**	(Smaling et al., 1993)
Stover		0.58	0.03	2.67	(Lekasi et al., 1999)
Straw		0.4-1.4	0.04-0.4	0.4-2.4	(Nijhof, 1987)
Banana (*Musa* sp.)					
Residue		0.15	0.2	0.48	(Smaling et al., 1993)
Leaf		2.75	0.097	4.85	(Lekasi et al., 1999)
Leaf	Central Kenya	1.3	0.1	1.72	ORD
Leaf	West Kenya	**2.5**	**0.13**	**2.66**	ORD
Trunk	West Kenya	**0.73**	**0.18**	**4.1**	ORD
Trunk	Uganda	0.47	0.06	3.84	ORD
Stem		1.01	0.069	7.7	(Lekasi et al., 1999)
Peels		**1.16**	**0.64**	**4.63**	(Lekasi et al., 1999)
Soybean (*Glycine max*)					
leaf	Kenya	**3.47**	**0.18**	**1.57**	ORD
Straw		0.4-1.7	0.1-0.5	0.6-3.0	(Nijhof, 1987)
Straw		**0.6**	**0.2**	**0.9**	(Nijhof, 1987)

APPENDIX X: (continued)

Plant part	**Country**	**N (%)**	**P (%)**	**K (%)**	**Source**
Bean (*Phaseolus* sp.)					
Residue		0.85	0.08	0.95	(Smaling et al., 1993)
Trash		2.53	0.16	1.85	(Lekasi et al., 1999)
Leaf		**3.72**	**0.26**	**2.75**	(Sanginga and Woomer, 2009)
Leaf		3.3	0.26	2.75	ORD
Stover		**0.99**	**0.11**	**1.93**	(Sanginga and Woomer, 2009)
Stover		0.77	0.06	1.31	ORD
Straw		0.8-2.3	0.08-0.4	0.85-3.7	(Nijhof, 1987)
Themeda sp.					
Whole plant	South India	**0.55**	**0.056**	**0.48**	(Paliwal and Manoharan, 1987)
Whole plant (average)	Australia	0.35	0.024	NA	(Norman, 1963)
Sugarcane (*Saccharum officinarum*)					
Residues		1.34	1.04	**0.6**	(Nair, 2010)
Residues		0.31	0.12	0.42	(Smaling et al., 1993)
Leaf		**1.21**	**0.14**	**1.16**	(Bokhtiar et al., 2008)
Leaf		0.55-1.7	0.1-0.3	0.4-2.4	(Nijhof, 1987)
Tephrosia vogelii					
Na		**3.01**	**0.18**	**0.9**	(Bucagu et al., 2013)
Na		2.5	0.19	1.1	(Drechsel et al., 1996)
Coffee pulp					
Na		3.73	0.17	5.4	(Nair, 2010)
Na		2.8	0.56	4.24	(van der Vossen, 2005)
Na		**3.7**	**0.4**	**6.5**	(van der Vossen, 2005)

Appendix 2.5: Nutrient contents of applied compost and manure according to different literature sources. ORD = Organic Resource Database (Palm et al., 2001), available at PPS: office.pp@wur.nl

	N (%)	P (%)	K (%)	Source
Compost				
	2.6	**1.49**	**2.13**	**ORD**
	1.82	1	1.51	(Sanginga and Woomer, 2009)
Cattle manure				
	2.5	0.49	5.56	(Nair, 2010)
	1.00	0.75	1.50	(Rufino et al., 2007)
	0.78	0.11	0.23	(Harris, 2002)
	2.1	0.26	1.37	(Henao and Baanante, 1999)
	0.98	0.22	0.85	(Sanginga and Woomer, 2009)
	1.3	**0.6**	**1.4**	(van der Vossen, 2005)
Goat manure				
	2.66	1.7	4.04	(Nair, 2010)
	2.80	**0.60**	**2.40**	(Harris, 2002)
	1.5	0.4	0.53	(Sanginga and Woomer, 2009)
	2.8	0.28	2.0	(Henao and Baanante, 1999)
Sheep manure				
	1.42	0.19	0.49	(Harris, 2002)
	1.28	0.47	5.7	(Sanginga and Woomer, 2009)
	2	**0.2**	**1.7**	(Henao and Baanante, 1999)
Poultry manure				
	3.54	1.4	**1.29**	(Nair, 2010)
	1.03	**0.22**	**1.93**	(Harris, 2002)
	2.88	1.58	2.25	(Sanginga and Woomer, 2009)
	1.6	0.37	0.83	(Henao and Baanante, 1999)
Pig manure				
	2.7	NA	NA	(Vanlauwe et al., 2002)
	0.2	1.19	0.49	(Sanginga and Woomer, 2009)
	0.6	**0.14**	**0.29**	(Henao and Baanante, 1999)
Rabbit manure				
	1.6	**0.4**	**0.5**	(Sanginga and Woomer, 2009)
	1.51	NA	NA	(Ferreras et al., 2005)

Appendix 2.6: The R code of the SAFERNAC model

```
# STEP 1: Potential soil supply of nutrients.
soil_supply_SAF <- function (soilparam, soilchem, inputs, dens)
# soilparam:      the soil parameter values
# soilchem:       the SOIL variables
# inputs:         the INPUT varibles
# dens:           the tree density
{
 with(c(soilparam, soilchem, inputs, dens),
    {
     # pH correction factors (f) for N, P, K
     fN      <- slN *pH + icN
     fP      <- icP + sl1P * pH + sl2P * (pH ** 2)
     fK      <- slK * pH + icK

     # Potential N, P and K supply in kg/ha
     soilN   <- fN * betaN * SOC                + recN * inputINN          + recN * relefN * inputON
     # Note: Equation 2a was selected for calculating SAN in the first step of the model and not equation 2b.
         # In (Maro et al., 2014a) it is unclear when each equation is most suitable, but according to
         # (Janssen et al., 1990) when the C:N ratio is 10, both equations are equivalent. The average C:N ratio
         # of the studied soils was 7.4, therefore potential supply of N could only be calculated as a function of
         # SOC.
     soilP   <- fP * alfaP * SOC + betaP * brayP      + recP * inputINP                    + recP * relefP * inputOP
     soilK   <- (fK * alfaK * exchK) / SOC            + recK * inputINK                    + recK * relefK * inputOK

     # Density correction
     fD      <- -0.06 * (NrTrees / 1000) ** 2 + 0.5 * (NrTrees / 1000)

     # Potential supply corrected with the tree density
     soilN_cor <- soilN * fD
     soilP_cor <- soilP * fD
     soilK_cor <- soilK * fD

     # max yield in kg dry matter per ha
     yieldmax  <<- 4500
     # Note: In the original model, the maximum yield is calculated with the equation:
         # Yieldmax = NrTrees * (2.2 - 0.15 * (NrTrees/1000))
         # However, applied to the plant density of 2000 trees per ha, the maximum yield can only be 3.8 tons
         # per ha, which is lower than the observed. For this reason, this equation was not used in the model.
         # Instead the maximum yield was set manually to the determined value.
     return(data.frame(fN=fN, fP=fP, fK=fK, fD=fD, soilN=soilN, soilP=soilP, soilK=soilK,
                soilN_cor = soilN_cor, soilP_cor = soilP_cor, soilK_cor = soilK_cor, yieldmax=yieldmax))
    })
}

# STEP 2a: Actual uptake
nutrient_uptake_SAF <- function(S1=NA, S2=NA, d1=NA, a1=NA, d2=NA, a2=NA)
{
 # N, P and K uptakes based on QUEFTS
```

```
  if (S1 < S2 * a2 / d1)
  {
   uptakeX_givenY = S1
  }
  else if (S1 > (S2 * (2 * d2 / a1 - a2 / d1)))
  {
   uptakeX_givenY = (S2 * d2 / a1)
  }
  else
  {
   uptakeX_givenY = S1 - 0.25 * (S1 - S2 * (a2 / d1))**2 / (S2 * (d2 / a1 - a2 / d1))
   }
  return(uptakeX_givenY)
}

# STEP 2b
actual_uptake_SAF <- function(supply, cropparam)
# supply:         the result of step 1
# cropparam:      the crop physiological efficiency values
{
  with(c(supply, cropparam),
     {
      UNP <- nutrient_uptake_SAF(S1 = soilN_cor, S2 = soilP_cor, d1 = dN, a1 = aN, d2 = dP, a2 = aP)
      UNK <- nutrient_uptake_SAF(S1 = soilN_cor, S2 = soilK_cor, d1 = dN, a1 = aN, d2 = dK, a2 = aK)
      UN  <- min(UNP, UNK)
      UPN <- nutrient_uptake_SAF(S1 = soilP_cor, S2 = soilN_cor, d1 = dP, a1 = aP, d2 = dN, a2 = aN)
      UPK <- nutrient_uptake_SAF(S1 = soilP_cor, S2 = soilK_cor, d1 = dP, a1 = aP, d2 = dK, a2 = aK)
      UP  <- min(UPN, UPK)
      UKN <- nutrient_uptake_SAF(S1 = soilK_cor, S2 = soilN_cor, d1 = dK, a1 = aK, d2 = dN, a2 = aN)
      UKP <- nutrient_uptake_SAF(S1 = soilK_cor, S2 = soilP_cor, d1 = dK, a1 = aK, d2 = dP, a2 = aP)
      UK  <- min(UKN, UKP)

      return(data.frame(UN=UN, UP=UP, UK=UK))
     })
}

# STEP 3: Yield ranges per nutrient.
max_min_yields_SAF <- function(uptake, cropparam)
# uptake:         the result of step 2
{
  with(c(uptake, cropparam),
     {
      YNA <- UN * aN
      YND <- UN * dN
      YPA <- UP * aP
      YPD <- UP * dP
      YKA <- UK * aK
      YKD <- UK * dK

      return(data.frame(YNA=YNA, YND=YND, YPA=YPA, YPD=YPD, YKA=YKA, YKD=YKD))
```

```
    })
}

# STEP 4.1b: Overlapping yield ranges per pair of nutrients.
yield_nutrients_combined_SAF <- function(U1=NA, d1=NA, a1=NA, Y2A=NA, Y2D=NA, Y3D=NA)
{
 YxD = min(Y2D, Y3D)

 if (U1 == 0 || YxD == 0)
 {   Y12 = 0   }
 else
 {   Y12 = Y2A +
    (2 * (YxD - Y2A) * (U1 - Y2A / d1)) / (YxD / a1 - Y2A / d1) - (YxD - Y2A) * (U1 - Y2A / d1)**2 / (YxD / a1 - Y2A /
d1)**2   }
 return(Y12)
}

# STEP 4b: # Final yield calculated based on the availability of pairs of nutrients
final_yield_SAF <- function(uptake, cropparam, yieldrange)
# yieldrange:       the result of step 3
{
 with(c(uptake, cropparam, yieldrange),
    {
     YNP <- yield_nutrients_combined_SAF(U1 = UN, d1 = dN, a1 = aN, Y2A = YPA, Y2D = YPD, Y3D = YKD)
     YNK <- yield_nutrients_combined_SAF(U1 = UN, d1 = dN, a1 = aN, Y2A = YKA, Y2D = YKD, Y3D = YPD)
     YPN <- yield_nutrients_combined_SAF(U1 = UP, d1 = dP, a1 = aP, Y2A = YNA, Y2D = YND, Y3D = YKD)
     YPK <- yield_nutrients_combined_SAF(U1 = UP, d1 = dP, a1 = aP, Y2A = YKA, Y2D = YKD, Y3D = YND)
     YKN <- yield_nutrients_combined_SAF(U1 = UK, d1 = dK, a1 = aK, Y2A = YNA, Y2D = YND, Y3D = YPD)
     YKP <- yield_nutrients_combined_SAF(U1 = UK, d1 = dK, a1 = aK, Y2A = YPA, Y2D = YPD, Y3D = YND)

     yieldM <-yieldmax
     YE   <- max(min(mean(c(YNP, YNK, YPN, YPK, YKN, YKP)), yieldM),0)

     return(YE)
    })
}

# All steps integrated in one function
safernac <- function(soilparam, cropparam, soilchem, inputs=NULL, dens)
{
 with(c(soilparam, cropparam, soilchem, inputs, dens),
    {
     # Step 1: potential supplies
     supply       <- soil_supply_SAF(soilparam = soilparam, soilchem = soilchem, inputs = inputs, dens = dens)

     # Step 2: actual uptakes
     uptake       <- actual_uptake_SAF(supply = supply, cropparam = cropparam)

     # Step 3: yield_ranges
     yield_ranges  <- max_min_yields_SAF(uptake = uptake, cropparam = cropparam)
```

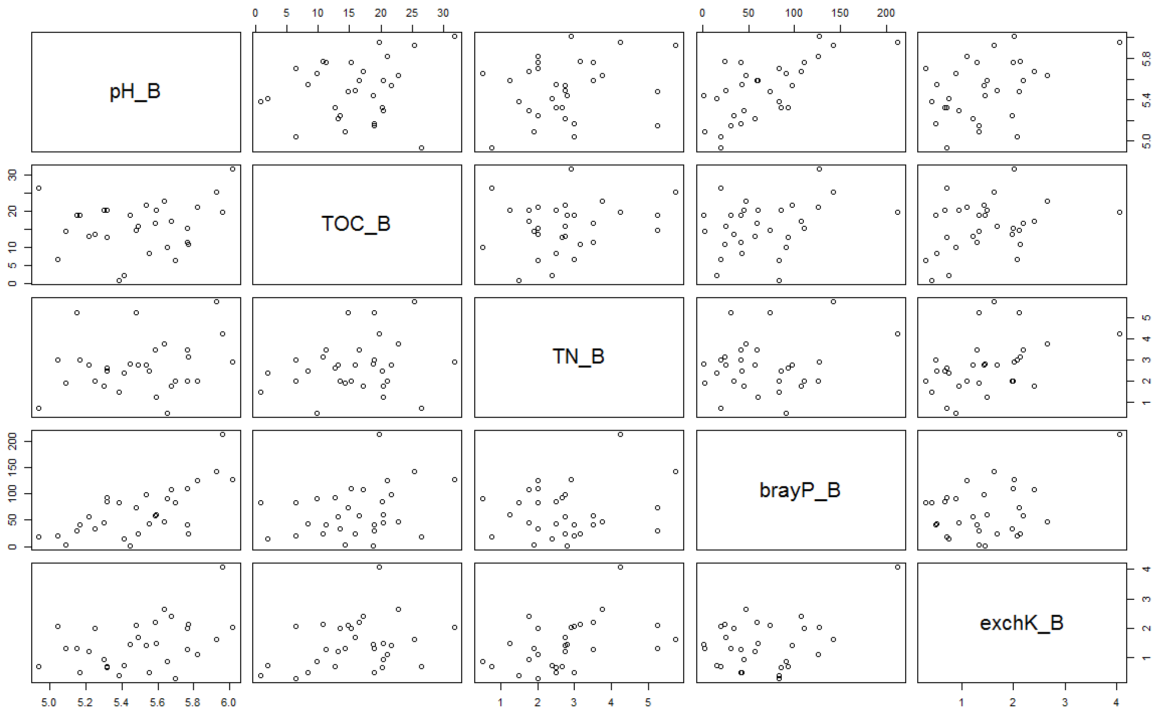
```
        # Step 4: final yield
        final_yield   <- final_yield_SAF(uptake = uptake, cropparam = cropparam, yieldrange = yield_ranges)

        saf_outcome   <- cbind(supply,uptake,yield_ranges,final_yield)

        return(saf_outcome)
        })
}
```

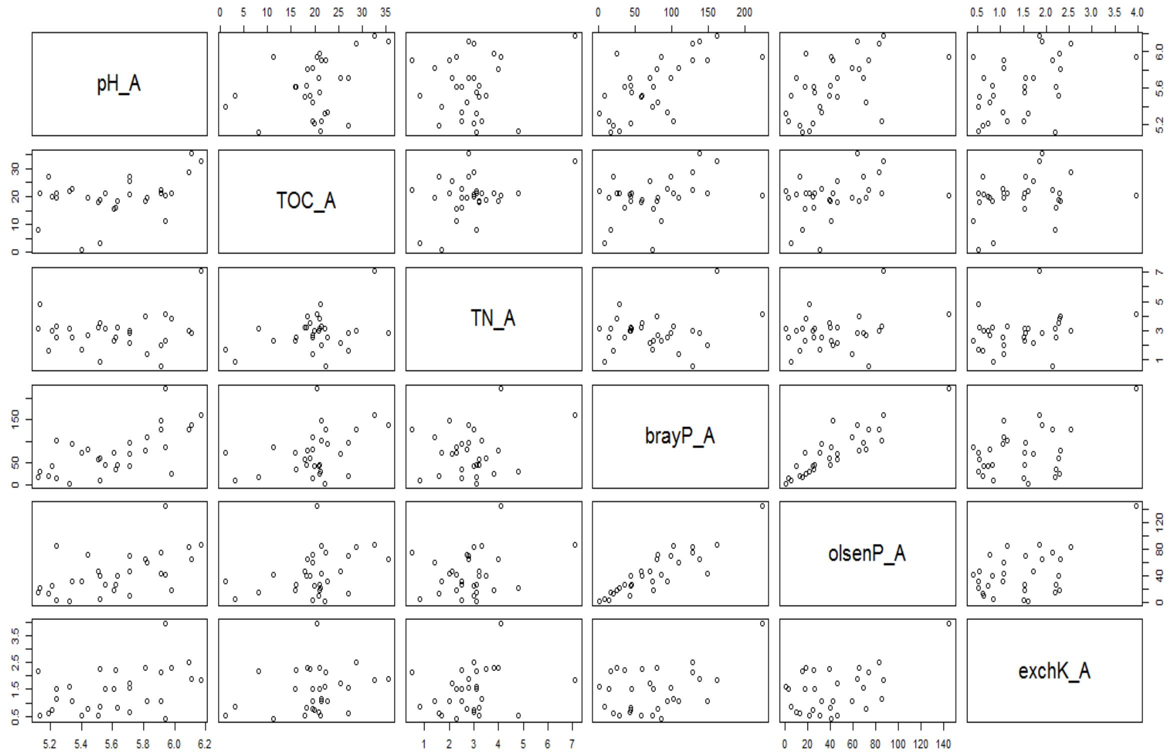
Appendix 2.7: The default values of the soil model parameters and the calibration ranges. NC = not calibrated

Parameter	Initial Value	Calibration range
dK	24	24 - 102
aK	8	8 - 18
dP	120	92 - 120
aP	40	22 - 40
dN	21	21 - 84
aN	7	7 - 20
alfaN	50	20 - 80
betaN	5	1 - 10
alfaP	0.25	0.1 – 0.4
alfaK	400	350 - 450
betaP	0.5	0.3 – 0.8
recN	0.7	0.3 – 0.5
recP	0.1	NC
recK	0.7	NC
relefN	0.6	0.2 – 0.6
relefP	0.87	NC
relefK	1	NC
slN	0.25	NC
icN	-0.75	NC
icP	-17	NC
sl1P	6	NC
sl2P	-0.5	NC
slK	-0.2	NC
icK	2	NC

Appendix 3: Results

Appendix 3.1: Correlations between soil variables before (B) and after (A) the establishment of Tephrosia





Appendix 3.2: Potential supplies (SN, SP, SK) and actual uptakes (UN, UP, UK) in regular fields (RF) during the initial evaluation. The most limiting nutrient(s) per farm are indicated with red

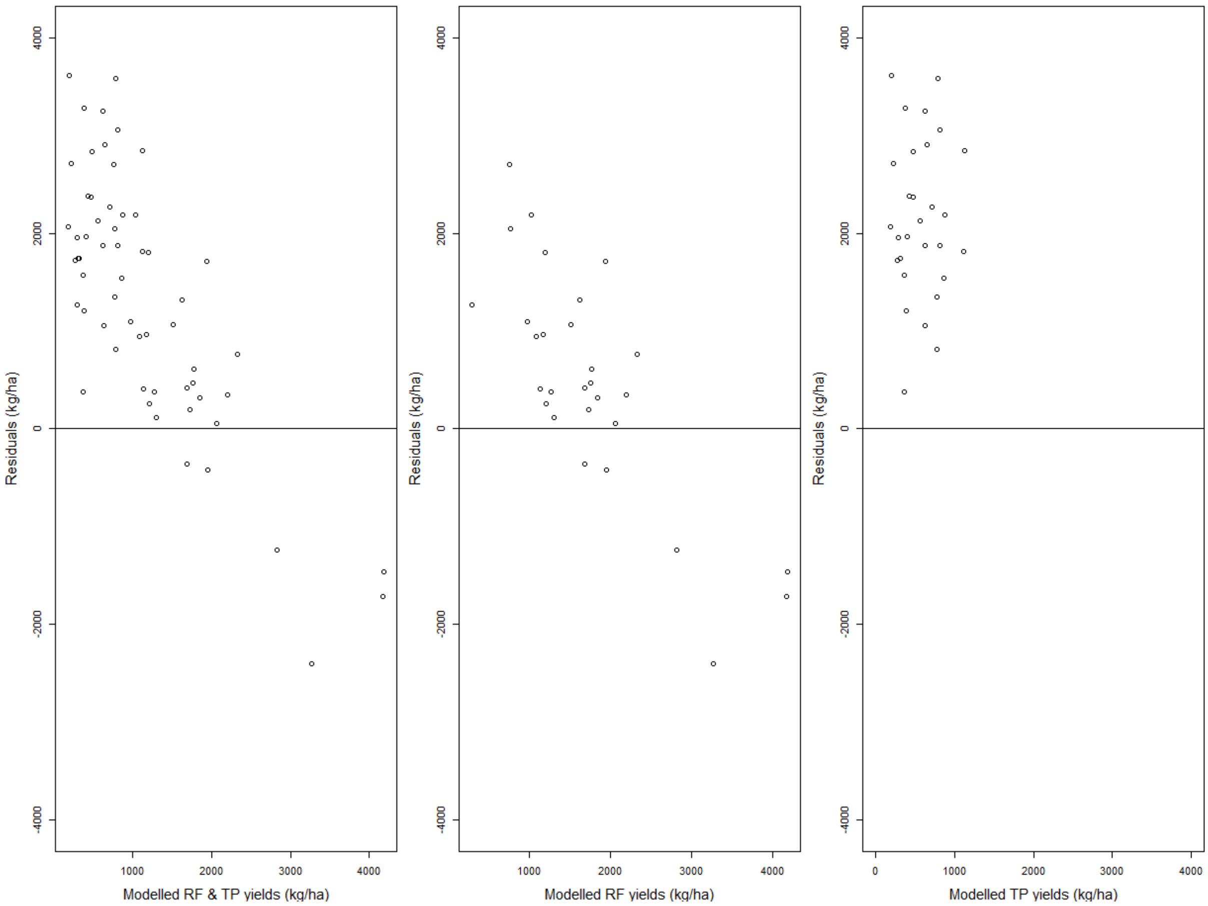
FieldNr	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)	Yield (kg/ha)
Regular Fields							
1	85.1	18.6	118.3	82.9	17.5	107.3	1274.8
2	69.6	7.1	205.3	62.2	7.0	105.8	776.9
3	91.3	45.7	154.5	90.8	36.1	135.3	1685.9
4	80.0	13.0	132.8	76.2	12.6	115.1	1134.6
5	128.0	10.6	288.3	110.0	10.5	158.6	1195.7
6	171.9	13.3	336.3	145.4	13.3	197.1	1510.2
7	194.0	17.3	454.4	169.5	17.2	258.6	1938.9
8	137.8	29.4	195.7	134.1	27.6	176.9	2059.5
9	45.8	25.3	41.9	44.0	19.3	40.0	763.9
10	85.5	13.2	138.9	81.0	12.8	119.5	1174.5
11	279.0	20.3	839.4	232.4	20.3	305.1	2330.2
12	113.0	36.9	117.3	109.7	32.5	110.5	1730.0
13	90.7	86.3	107.0	88.8	47.5	99.4	1690.7
14	266.8	51.8	510.9	257.9	49.2	435.6	4165.8
15	55.8	36.5	56.5	54.1	25.9	53.4	978.5
16	49.7	33.1	254.1	49.7	23.3	130.5	1033.0
17	86.4	33.6	203.9	86.1	28.6	164.3	1620.4
18	133.6	18.9	223.0	125.3	18.4	186.7	1760.7
19	114.7	18.8	275.4	109.2	18.1	216.0	1772.1
20	190.2	39.5	541.8	184.7	37.2	408.6	3273.6
21	108.4	41.8	151.3	107.0	35.6	137.2	1845.8
22	na	na	na	na	na	na	na
23	111.8	31.2	252.7	110.3	28.2	206.3	1957.7
24	275.4	10.1	570.3	169.3	10.1	152.1	1213.8
25	151.6	24.9	272.5	144.5	24.0	232.4	2200.4
26	191.4	57.7	185.2	184.9	51.7	175.8	2823.1
27	257.9	63.1	453.1	253.0	58.3	393.8	4182.7
28	94.4	52.3	62.6	87.9	35.0	61.2	1303.5
29	71.1	22.0	77.1	69.3	19.6	72.3	1088.6
30	75.2	2.6	36.0	43.6	2.6	28.6	298.3

Appendix 3.3: Potential supplies (SN, SP, SK) and actual uptakes (UN, UP, UK) in Tephrosia plots (TP) during the initial evaluation. The most limiting nutrient(s) per farm are indicated with red

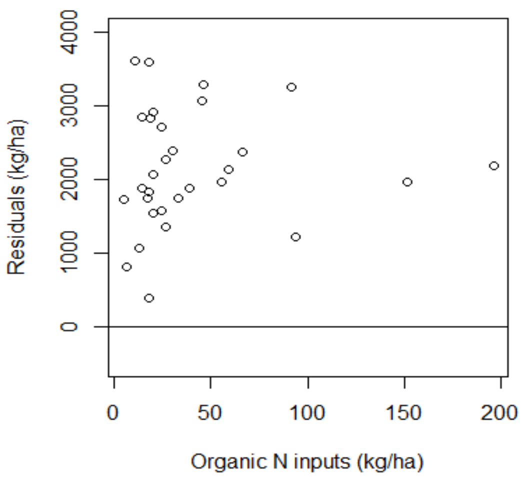
FieldNr	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)	Yield (kg/ha)
Tephrosia plots							
1	117.4	17.6	17.0	58.3	10.1	17.0	407.5
2	57.7	6.0	104.0	51.8	5.9	76.3	633.2
3	97.5	44.8	33.7	80.0	20.2	33.7	775.9
4	81.9	11.1	50.6	75.5	10.5	48.8	811.9
5	63.7	8.3	96.1	59.1	8.1	80.8	783.7
6	101.2	9.5	8.3	28.5	5.0	8.3	199.6
7	93.6	13.9	20.6	64.4	10.3	20.6	481.3
8	120.3	26.3	19.7	67.2	11.8	19.7	472.0
9	95.4	25.2	35.4	79.8	18.3	35.3	789.8
10	98.9	12.0	29.0	77.1	10.4	28.9	623.1
11	92.3	14.5	42.4	81.1	13.0	42.0	816.5
12	101.3	35.4	9.3	31.9	5.6	9.3	223.6
13	109.0	84.5	50.6	95.9	30.3	50.2	1126.9
14	155.3	44.0	36.8	110.8	22.1	36.8	872.7
15	92.6	36.3	23.9	68.7	14.3	23.9	563.4
16	56.5	31.8	144.2	56.5	24.1	113.2	1120.8
17	83.1	32.7	12.3	42.1	7.4	12.3	295.0
18	94.4	17.9	7.7	26.4	4.6	7.7	184.9
19	84.9	17.7	29.6	69.9	13.8	29.6	654.6
20	107.0	37.0	16.1	55.0	9.6	16.1	385.2
21	110.8	40.9	17.9	61.3	10.8	17.9	430.1
22	98.9	20.0	13.2	45.2	7.9	13.2	316.5
23	89.9	30.1	39.3	78.2	21.1	39.1	864.0
24	100.4	3.5	21.2	59.8	3.4	19.9	369.7
25	105.8	23.3	26.8	77.9	15.2	26.8	629.7
26	145.4	54.2	15.4	52.9	9.3	15.4	370.2
27	133.9	58.9	15.9	54.7	9.6	15.9	382.6
28	115.7	51.6	13.3	45.7	8.0	13.3	320.1
29	114.5	21.8	31.0	86.6	15.9	31.0	715.5
30	78.8	2.5	27.7	42.1	2.4	23.4	279.3

Appendix 3.4: Error exploration

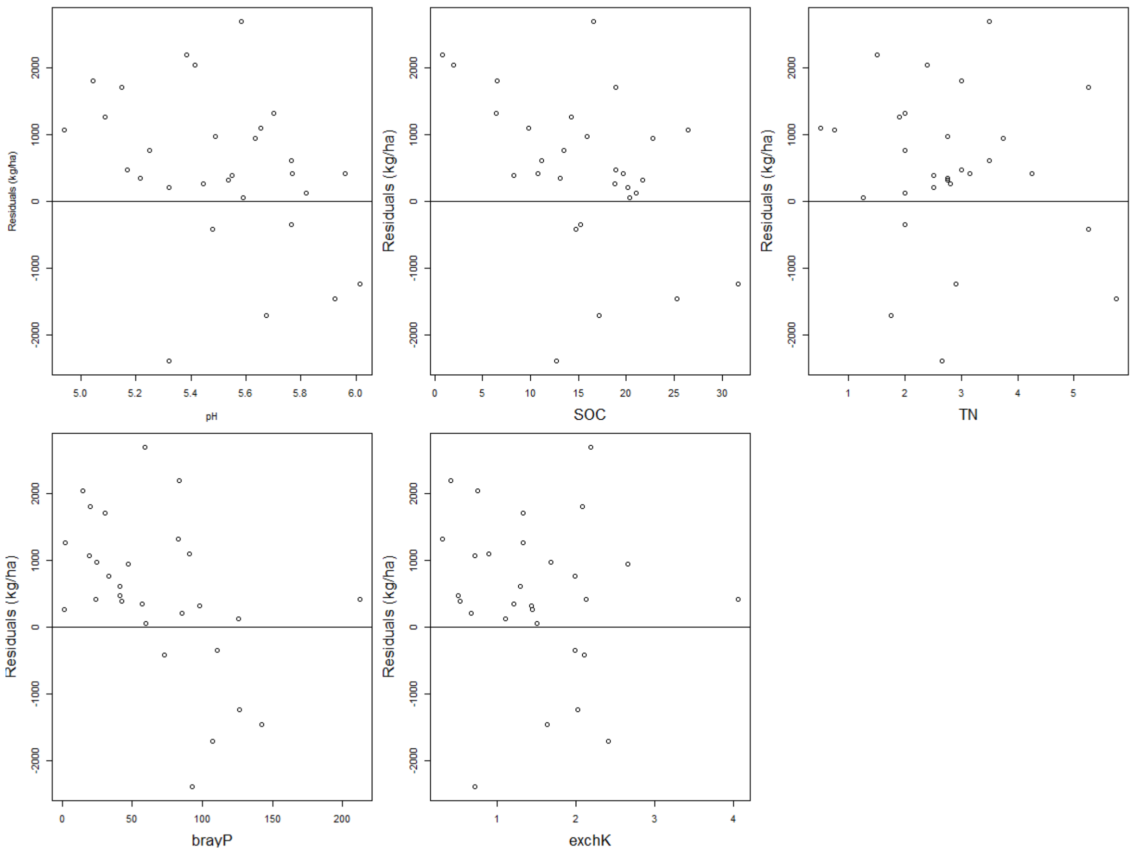
Residuals against modelled yields for all fields and plots (left), for only the RF (middle) and only the TP (right)



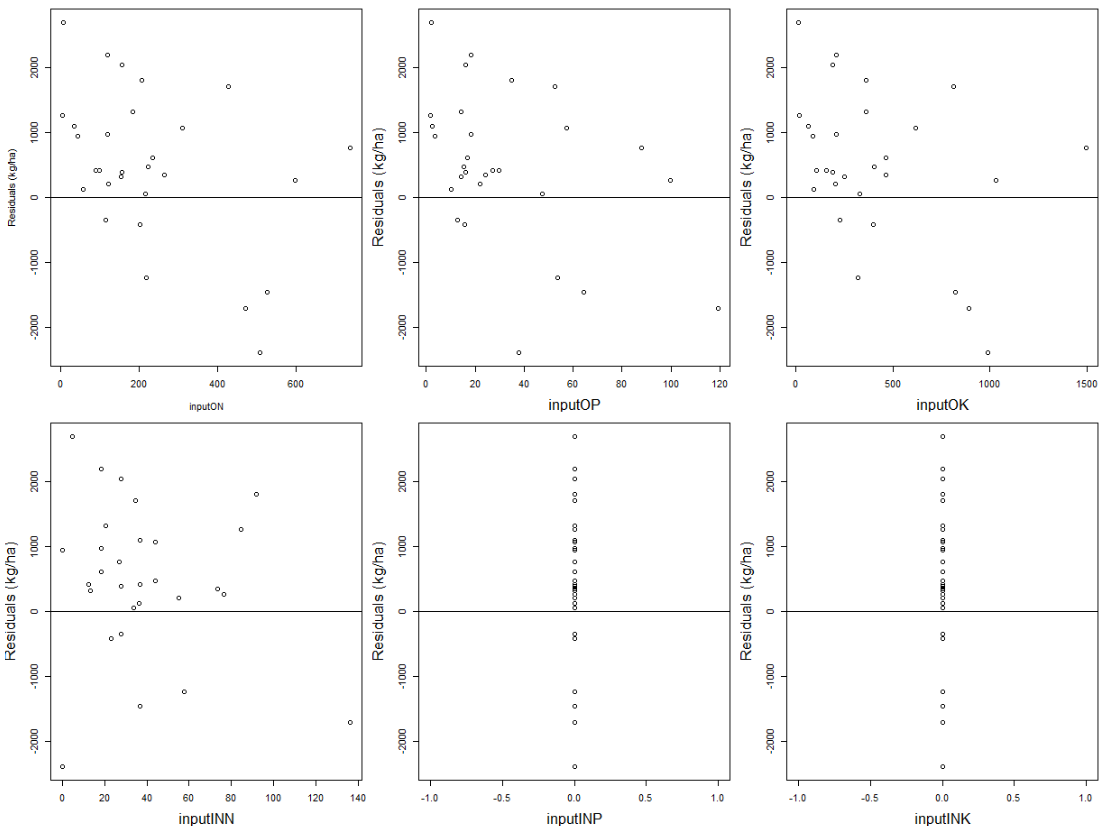
Residuals of the TP data against the amount of N fixed by the Tephrosia



Residuals of RF against soil fertility parameters

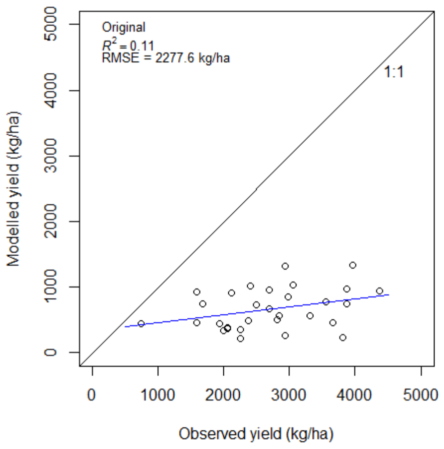


Residuals of RF against added inputs

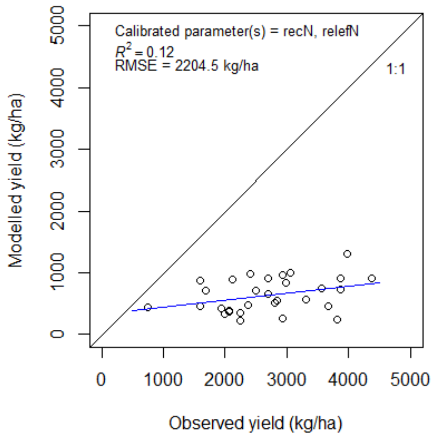


Appendix 3.5: The model evaluation plots in every step of the calibration

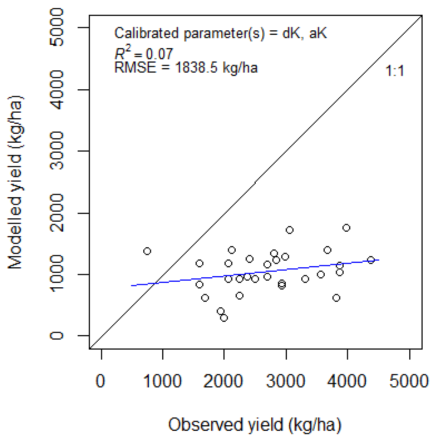
Original



Step 1: recN, relefN



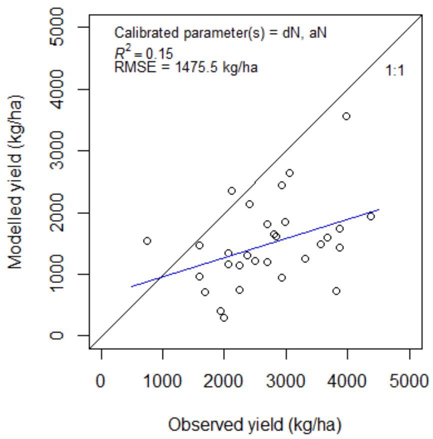
Step 2: aK, dK



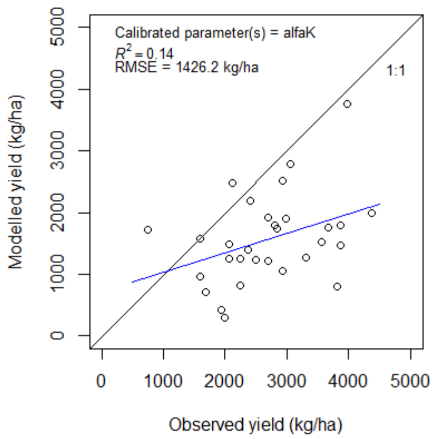
Step 3: aP, dP

No change

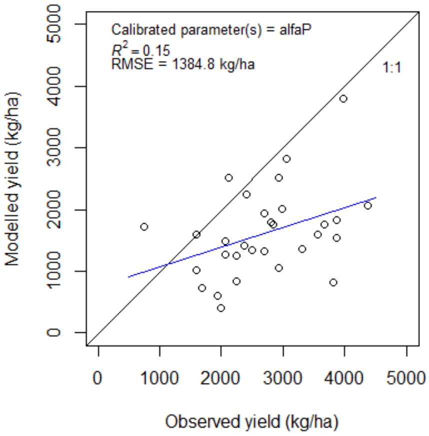
Step 4: dN, aN



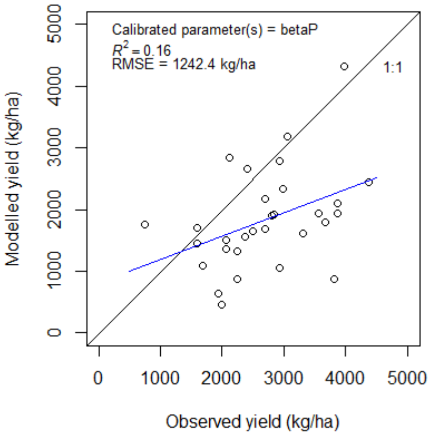
Step 5: alfaK



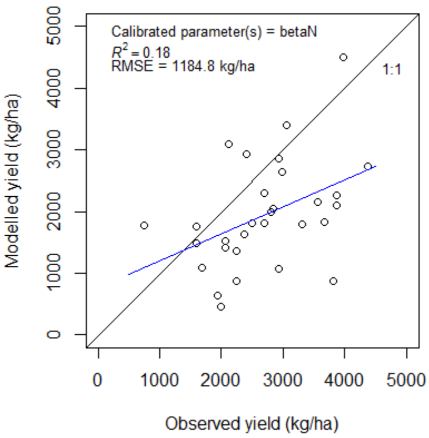
Step 6: alfaP



Step 7: betaP



Step 8: betaN



Step 9: alfaN

No change

Appendix 3.6: Potential supplies (SN, SP, SK) and actual uptakes (UN, UP, UK) in regular fields (RF) during the final evaluation. The most limiting nutrient(s), if any, per farm are indicated with red

FieldNr	SN (kg/ha)	SP (kg/ha)	SK (kg/ha)	UN (kg/ha)	UP (kg/ha)	UK (kg/ha)	Yield (kg/ha)
1	74.7	29.2	120.4	68.9	28.7	104.2	2682.0
2	43.6	10.6	218.3	37.3	10.6	70.9	1203.7
3	107.8	72.5	158.7	104.5	69.0	148.9	4500.0
4	86.1	19.7	139.2	72.5	19.6	104.2	2164.1
5	91.8	15.6	300.3	71.1	15.6	103.7	1819.7
6	161.9	19.0	337.4	106.2	19.0	126.6	2265.3
7	155.6	25.7	457.0	119.3	25.7	171.1	3006.1
8	146.4	45.2	198.2	130.8	44.8	169.5	4415.8
9	84.5	40.4	46.3	78.4	37.9	45.4	2646.5
10	100.4	20.4	142.5	82.2	20.4	107.2	2275.6
11	180.3	29.1	844.7	137.1	29.1	193.8	3410.3
12	128.6	58.2	118.5	120.7	56.7	112.2	4476.2
13	129.2	137.0	113.4	124.2	123.6	110.0	4500.0
14	210.9	78.2	515.5	193.5	77.1	395.8	4500.0
15	68.9	58.2	59.5	66.2	54.0	57.8	3119.7
16	28.8	52.2	272.1	28.8	42.1	134.3	2301.9
17	68.8	53.3	205.4	67.2	50.0	175.5	4016.3
18	128.5	29.7	224.0	108.6	29.6	163.4	3279.8
19	101.8	29.4	279.1	89.9	29.2	182.1	3222.9
20	133.2	61.7	543.8	125.3	60.2	369.4	4500.0
21	132.9	66.3	153.6	125.9	64.4	143.8	4500.0
22	na	na	na	na	na	na	na
23	108.9	49.2	257.6	102.2	48.1	211.7	4500.0
24	207.6	12.3	573.0	73.6	12.3	81.8	1471.8
25	123.5	38.9	275.9	110.7	38.6	206.4	4085.4
26	236.8	90.2	187.1	217.9	88.1	176.9	4500.0
27	234.6	98.5	455.1	218.4	96.5	384.9	4500.0
28	135.3	83.2	64.3	123.5	74.5	63.7	4343.5
29	120.6	35.1	81.0	106.7	34.4	75.9	3092.2
30	89.8	4.0	39.4	24.2	4.0	25.3	482.6

Appendix 3.7: Fertilization recommendations per farm (for application rates, see text)

FieldNr	None	Only N	Only P	Only K	NP	NPK100	NPK150	NK	NP150K	NP300K	NP450K	PK	N150PK	N200PK
1	1305	1333	1375	3190	1397	4500	4500	3621	4500	4500	4500	4500	4500	4500
2	658	743	1205	658	3416	3762	3880	743	2085	3244	4144	1230	3413	3892
3	2554	2697	2616	4500	2747	4500	4500	4500	4500	4500	4500	4500	4500	4500
4	1946	2174	2559	2504	2811	4500	4500	2596	3769	4500	4500	4500	4500	4500
5	1236	1409	2198	1292	3848	4229	4358	1433	2733	3807	4500	2544	4029	4396
6	724	724	756	2109	756	4229	4500	2161	3370	4350	4500	4380	4500	4500
7	807	807	834	2392	834	4200	4500	2579	3671	4500	4500	4220	4500	4500
8	1914	1956	1996	4500	2030	4500	4500	4500	4500	4500	4500	4500	4500	4500
9	2479	3018	2918	3802	3363	4500	4500	4442	4500	4500	4500	4500	4500	4500
10	421	4010	421	421	4500	4500	4500	4500	4500	4500	4500	421	3422	4500
11	2078	2561	2837	2788	3442	4500	4500	3088	4123	4500	4500	4451	4500	4500
12	1245	1257	1246	4248	1258	4500	4500	4500	4500	4500	4500	4500	4500	4500
13	4390	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500	4500
14	2360	2388	2383	4500	2410	4500	4500	4500	4500	4500	4500	4500	4500	4500
15	1578	1603	1579	4500	1604	4500	4500	4500	4500	4500	4500	4500	4500	4500
16	2257	2654	2522	4019	2846	4500	4500	4500	4500	4500	4500	4500	4500	4500
17	1010	1031	1010	3710	1031	4500	4500	4500	4500	4500	4500	4196	4500	4500
18	1152	1170	1199	3047	1213	4479	4500	3478	4385	4500	4500	4457	4500	4500
19	1854	2035	2091	3331	2213	4500	4500	3721	4500	4500	4500	4500	4500	4500
20	1487	1508	1491	4500	1513	4500	4500	4500	4500	4500	4500	4500	4500	4500
21	1697	1704	1705	4500	1711	4500	4500	4500	4500	4500	4500	4500	4500	4500
22	1720	1788	1735	4500	1802	4500	4500	4500	4500	4500	4500	4500	4500	4500
23	2688	3130	3012	4469	3380	4500	4500	4500	4500	4500	4500	4500	4500	4500
24	677	677	1975	728	2184	3756	3946	728	2090	3314	4306	3724	3987	4175
25	950	951	952	3565	953	4500	4500	4235	4500	4500	4500	4500	4500	4500
26	1461	1461	1461	4500	1461	4500	4500	4500	4500	4500	4500	4500	4500	4500
27	1517	1517	1517	4500	1517	4500	4500	4500	4500	4500	4500	4500	4500	4500
28	1432	1437	1432	4500	1437	4500	4500	4500	4500	4500	4500	4500	4500	4500
29	909	909	918	3278	918	4500	4500	3643	4500	4500	4500	4500	4500	4500
30	1295	1388	2077	1579	2358	4100	4335	1615	2902	3954	4500	3957	4323	4500