Effect of timing and methods of mineral fertilizer application on Irish potato *(Solanum tuberosum L.)* performance in Musanze and Nyaruguru Districts, Rwanda

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DECLARATION

This thesis is my original work and has not been presented for the award of a degree in any other academic Institution.

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ACRONYMS AND ABBREVIATIONS

ADP	Adenosine diphosphate
AE	Agronomic Efficiency
AGRA	Alliance for Green Revolution in Africa
ANOVA	Analysis Of Variance
ASN	Ammonium Sulphate Nitrate
ATP	Adenosine Triphosphate
BMP	Best Management Practice
CAADP	Comprehensive Africa Agriculture Programme
CAN	Calcium Ammonium Nitrate
CEC	Cation exchange capacity
CIP	Centre International de la Pomme de terre/ Potato International Centrer
cm	Centimeter
CRF	Controlled-Release Fertilizer
CV	Coefficient of variation
DM	Dry Matter
DAE	Days After Emergence
DAP	Diammonium Phosphate
DAS	Days After Sowing
DCD	Dicyandiamide
DMRT	Duncan Multiple Range Test
FAO	Food and Agriculture Organization (of the United Nations)
FAOSTA	Food and Agriculture Organization of United Nations (Statistcs division)
F_X	Level of method (of mineral fertilizer application) factor
FYM	Farm Yard Manure
GM	Grand Mean

GDP	Gross Domestic Product
ha	Hectare
I FDC /ICSFAD	International Fertiliser Development Centre/International Centre for Soil Fertility and Agricultural Development
IPM	Integrated Pests Management
ISAR	Institut des Sciences Agronomiques du Rwanda
Kg	Kilogram
LAI	Leaf Area Index
L	Liter
LARMAT	Land Resource Management and Agricultural Technonology
Lb	Pound/ Unit for measuring weight; equal to 0.454kilograms
LSD	Least Significant Difference
m	Meter
MINAGRI	Ministry of Agriculture, Forestry and Livestock
MINECOFIN	Ministry of Finance and Economic Planning
MINIRENA	Ministry of Lands, Environment, Forests, Water and Mines
mm	Millimeter
NSP	Number of Stems (Shoots) per Plant
NBPT	n-butylthiophosphoric triamide
NGO	Non-Governmental Organisation
N.P.K	Nitrogen-Phosphorus-Potassium
^{O}C	Degree Celsius
ORTPN	Office Rwandais du Tourisme et des Parcs Nationaux
PAR	Photosynthetically Active Radiation
PE	Physiological Efficiency
PFP	Partial Factor Productivity
pH	Potential Hydrogen

RAB	Rwanda Agriculture Board
RCBD	Randomized Complete Block Design
RE	Rcovery Efficiency
SH	Stem Height
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TDM	Total Dry Matter
t	Ton
T_X	Level of timing (of mineral fertilizer application) factor
US	United States
%	Percent

ABSTRACT

Irish potato is among the most important tuber crops produced in Rwanda and is among priority crops on which the national programme of intensification and development of sustainable production systems is primarily focused, but so far its yield is still below the genetic potential. A field experiment was therefore conducted to investigate the effect of timing and methods of mineral fertilizer (N.P.K 17-17-17) application on growth, yield and yield components of Irish potato - cruza variety in Kibeho (Nyaruguru District) and Kinigi (Musanze District) during the long rainy season (mid-February - June) of 2012. The experiment was laid out as a RCBD with a factorial arrangement, and replicated three times. The factors were timing of fertilizer application (T_x); (i) T_1-100% of the fertilizer applied at planting time , (ii) T_2 - 50% of the fertilizer applied at planting and the remaining 50% applied at weeding time (two weeks after emergence) (iii) T_3 - 75% of the fertilizer applied at planting and 25% at weeding time (iv) T_4 - 50% of the fertilizer applied at planting and 50% at earthing up time (four weeks after emergence) and (v) T_5 - 75% of the fertilizer applied at planting and 25% at earthing up time and methods of fertilizer application (F_x) at two levels; (i) localised placement (F_2) and (ii) row banding (F_1). The treatments were; F_1T_1, F_1T_2, F_1T_3, F_1T_4, F_1 T_5, F_2 T_1, F_2T_2, F_2T_3, F_2T_4 and F_2T_5. Agronomic parameters; emergence rate, number of shoots per plant, stem height, canopy cover, number of tubers per plant, tuber grades and tuber yields, and soil chemical properties (soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable bases and CEC) were measured. Regarding times of application, the crop performed better in split than in single fertilizer application with potato yields (14.73 t ha^{-1} at Kibeho and 17.00 t ha^{-1} at Kinigi) and yield components being significantly higher in T_2 across fertilizer application methods. The Irish potato yields (13.81 t ha^{-1} at Kibeho and 16.09 tha^{-1} at Kinigi) and yield components were significantly higher with localised placement (F_2) than row banding (F_1) across the fertilizer times of application. The correlation between stem height, canopy cover and number of tubers per plant with tuber yield was positive and significant. Timing and methods of fertilizer application and their interactions had no significant effect ($P>0.05$) on the measured soil chemical properties. For enhanced Irish potato production, fertilizer should be applied in two splits, with the second portion applied at weeding time (two weeks after emergence), and using localized fertilizer placement method.

CHAPTER 1

1.0 Introduction

1.1 Background of the study

Irish potato (*Solanum tuberosum L.*) is grown and eaten in more countries than any other crop and in the global economy it is the fourth most important crop after maize, rice and wheat (Stephen, 1999). Irish potato, has a longstanding history in human nutrition. The crop is fairly new to Sub-Saharan Africa (SSA) where it was introduced in the 19th Century. Compared to other tuber crops, Irish potato has the highest protein to calorie ratio, and it is the highest producer of energy per hectare per day. The crop is adapted to a cool moist climate, and grows in the high altitudinal ecosystems of SSA where rainfall is well distributed for 3–4 months (CIP, 1982). In Sub-Saharan Africa, potatoes have become a preferred food in urban areas, and an important staple and cash crop in highland production zones of Cameroon, Kenya, Malawi, Nigeria, Rwanda and South Africa (FAO, 2006).

Irish potatoes have been cultivated in Rwanda for nearly a century, and most accounts trace introduction of the crop to the arrival of German missionaries in the late 19th century (Scott, 1988). The Irish potato falls in the category of priority crops to be promoted in Rwanda's farming zones where prevailing agro-ecological conditions match with Irish potato production requirements and subsequently considered as staple food and major source of revenue for people (MINAGRI, 2009). Potatoes grow well in several parts of the country mainly above elevations of 1800 m above sea level and some areas grow two or even three crops a year (MINAGRI, 2009).

The potato underpins Rwanda's food securit, and in the order of main food crops ranking comes fourth; banana (62.5%), sweet potatoes (17.9%), cassava (4.5%), Irish potatoes (4.3%), pulse (beans and pea, 3.9%), sorghum (2.9%), maize (1.4%), and the rest are paddy, wheat, soybean and groundnuts (MINAGRI, 2009). In Africa, Rwanda is currently classified among good producers of Irish potato with a general average yield of 9 t/ha over the whole country and more than the double is the average in Northern Rwanda (FAOSTA, 2007). This yield is however still very low compared to that reached in Uganda (25 t/ha on research station and 14.5 t/ha under farm conditions), Egypt (25 t/ha under farm conditions) and South Africa (34 t/ha under farm conditions) (Ferris, 2003), also in the USA (36 t/ha) and in Germany (33 t/ha) (FAO, 2008). This yield gap shows that there is even more room for improvement. This means that potential still exists for improvement of productivity.

Much investment has been made in research and development in an effort to improve Irish potato productivity of smallholder farmers. These efforts have focused on different aspects such as comparing different methods of fertilizer application vs broadcasting, placement and banding in Islamabad (Pakistan) (Mahmood *et al*., 2002); reviewing and summarizing potato fertilization research in Florida (Hochmuth and Hanlon, 2000), determining the most advantageous placement in which commercial fertilizers may be applied with respect to the potato seed piece (Cumings *et al.*, 1939) and assessing the effect of source, time and methods of nitrogen application on growth and yield components of potato in Kenya (Gathungu *et al.*, 2000).

In Rwanda, research focused on some agronomic practices. Regarding fertilizer application, the recommende rates are 30 t/ha of FYM and 0.3 t/ha of N.P.K 17-17-17 applied at ploughing and planting times, respectively. The recommended methods of fertilizer application are broadcasting and hole placement for FYM and N.P.K, respectively (MINAGRI, 2010). The recommended spacing is 30× 70 cm with potential to be adapted to variety, soil and weather conditions. The planting depth is around 10 cm (MINAGRI, 2010). Despite the efforts, the productivity of Irish potato farmers in Rwanda still really low (9 t/ha as average). The irish potato yield and yield components obtained are still below the genetic potential.This means that potential still exists for improvement of productivity by proper use of inputs such as fertilizers.The improvement of fertilizer use efficiency, by proper timing and right placement of mineral fertilizer may be the key to improve the crop performance under crop intensification system and in sustainable way.

1.2 Problem statement

In Rwanda, agriculture accounts for more than 90% of the labour force, yet remains unproductive and largely practiced on a subsistence level with farmers owing less than 1 hectare, which is too small to earn a living (Ministry of Finance and Economic Planning, 2000). This results in intense exploitation of the land, with no simultaneous application of corrective measures, most notably through fertilizer use. The net result has been a decline in land productivity and massive environmental degradation, contributing to rampant malnutrition amongst the Rwandan population (Ministry of Finance and Economic Planning, 2000). Kelly *et* *al.* (2002) estimated that less than 5% of farmers use fertilizer on less than 3 percent of cultivable land area in Rwanda. The current fertilizer application rate in Rwanda is among the lowest in Africa and on average amounts to a mere 8 kilograms of nutrients per hectare (Kelly *et al.*, 2002).

According to Gossens (2002), the sub-optimal Irish potato yields, in Rwanda, are caused by lack of knowledge about good cultural practices in general and inappropriate and low use of mineral fertilizer and herbicides in particular, among other facors. He also said that poor crop-husbandry, harvesting and post-harvesting technology is the major constraint for Irish potato chain development on supply side. According to Valerie *et al.* (2001), one of the cause of the limited use of mineral fertilizer in Rwanda is insufficient knowledge of the benefits and of how to use the mineral fertilizers (information got from 53% of the 88% who were non-users, which represents 47% of all farm households). Mellor (2001) indicated that one of the requirements for rapid growth of Irish potato production is improvement of production technology to optimizer fertilizer use efficiency. The author continued by saying that Irish potato production can grow quickly due to its high response to fertilizer, and if farmers already have enough knowledge of fertilizer use and improved crop husbandry.

One of the challenges of Irish potato production, as with any other crop, is the efficient management of fertilizers in general, and nitrogen fertilizers in particular. N is the most limiting factor in crop production (Stark and Love, 2003 and Westermann, 2005). Potatoes are especially sensitive to N deficiencies and excesses (Stark and Love, 2003). In Rwanda, fertilizer use effectiveness is low since the quality and quantity of information available on fertilizer use (application rate, application time, application methods, plant nutrient ratios) is inadequate and most farmers are unable to afford or access the comprehensive package of complementary practices needed to get the most out of the fertilizer (e.g., improved seeds, diseases and pests management, water management, …)(MINAGRI, 2009).

Greater synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency, especially for N. Split applications of N during the growing season, rather than a single, large application prior to planting, are known to be effective in increasing N use efficiency (Cassman *et al*., 2002). Application method has always been critical in ensuring if fertilizer nutrients are used efficiently. Determining the right placement is as important as determining the right application rate. Placement decisions depend on the crop and soil conditions, which interact to influence nutrient uptake and availability (Roberts, 2008). In Rwanda, relatively very little work has been carried out on fertililiser use efficiency in general, and on Irish potato fertilizer use efficiency under different soils and climatic conditions in particular.

1.3 Justification of the study

Increased and efficient fertilizer use can help reverse the declining trends in per capita crop production experienced in many SSA countries, without having adverse environmental consequences (Bumb, 1991). Adequate and timely fertilizer applications will not only supply necessary nutrients and improve crop yields, but will also provide relatively higher amounts of crop residue, which can be used as organic matter to improve soil health and prevent soil degradation (Bumb 1991). Given the low levels of fertilizer use in SSA and the contribution of fertilizers to increasing crop yields and land productivity, the increased judicious use of fertilizers has great regional potential for boosting food production and promoting agricultural development (Mwangi, 1996). The increased and judicious use of fertilizer is necessary to achieve sustainable increases in agricultural productivity necessary to meet the CAADP target of 8 percent annual agricultural growth and achieve the first Millennium Development Goal of halving poverty and hunger by 2015 in Rwanda (MINAGRI, 2009).

To contribute to food security and sustainable production system through Irish potato production performance, many options are possible and one of them can be defined in terms of fertilizer use efficiency improvement: optimizing profit and production per unit area without compromising environmental sustainability. The determination of appropriate time and method of mineral fertilizer (N-P-K, 17-17-17) application, case of the study, is expected to contribute significantly to enhanced irish potato performance.

Efficient fertilization is synonymous with the minimization of nutrient losses to the environment, without sacrificing crop yields. Careful attention must be paid to all aspects of product quality to maximize the efficiency of fertilization. Excess nutrients, especially nitrogen, not taken up by the crop, are likely to be lost to the environment. Uneven fertilization means over-fertilization (pollution) of some areas, under-fertilization (loss of yield/quality) of others. Thus, the synchronization of nutrients availability and potato demand, through right time and method of fertilizer application, is recommended to optimize yield, tuber quality, and mineral nutrient efficient use without threatening sustainability of the system. Therefore, the study was significant because it was carried out to find out the right time and method of mineral fertilizer application leading to Irish potato production performance in Rwanda.

Adoption of the study findings is expected to enable Irish potato growers to match fertilizer application to crop requirement and to match soil supply to crop requirement spatially and temporally. By fertilizer use efficiency, farmers will contribute to soil and environment improvement and conservation, integrated nutrient management, yield and income increase, family and national economy improvement. Briefly they will enable the country to meet the millennium goals: to alleviate or to eradicate malnutrition, hunger and poverty.

The findings of this study were to benefit several groups of people. The communities of Irish potato growers may benefit by being empowered to sustainably exploit their environment and other resources thereby improving their economic status. The findings of the study also benefit the government agricultural research and extension services and other extension providers by identifying appropriate time and method of mineral fertilizer application on Irish potatoes. Policy makers in the government may benefit as they may also use findings to set policies aimed at Irish potatoes production and performance thus contributing to overall food security. Also policy makers, private sector and NGOs will be convinced by the findings of the study to invest more and under no or less economical risks in infrastructure and other sectors in favour of production of Irish Potatoes.

1.4 Objectives

1.4.1 Overall objective

To contribute towards enhanced irish potato *(Solanum tuberosum, Cruza variety)* performance in Musanze and Nyaruguru Districts (Rwanda) through synchronized timing and method of mineral fertilizer application.

1.4.2 Specific objectives

- To assess the effect of timing and methods of mineral fertilizer application on selected soil chemical properties (soil reaction, organic carbon, total nitrogen, available phosphorus, exchangeable bases and cations exchange capacity), under Irish potato production.
- To evaluate the effect of fertilizer application methods on Irish Potato (Cruza variety) performance.
- To assess the effect of timing of fertilizer application on Irish Potato (Cruza variety) performance.

1.5 Hypotheses

- Timing and methods of mineral fertilizer application influence selected chemical properties (soil reaction, organic carbon, total nitrogen, available phosphorus, exchangeable bases and cations exchange capacity) of the soil under Irish potato production.
- Mineral fertilizer application methods enhance Irish potato performance.
- Timing of mineral fertilizer application improves the performance of Irish potato.

CHAPTER 2

2.0 Literature review

2.1 Plant nutrition and fertilizer use

Plants use inorganic minerals for nutrition, whether grown in the field or in a container. Complex interactions involving weathering of rock minerals, decaying organic matter, animals, and microbes take place to form inorganic minerals in soil. Roots absorb mineral nutrients as ions in soil water. Many factors influence nutrient uptake for plants. Ions can be readily available to roots or could be "tied up" by other elements or the soil itself (Jones and Jacobsen., 2001). A large number of diverse materials can serve as sources of plant nutrients. These can be natural, synthetic, recycled wastes or a range of biological products including microbial inoculants. Nutrient sources are generally classified as organic, mineral or biological (FAO, 2006).

2.1.1 Fertilizer use

(i) Fertilizer use in Africa and agricultural productivity

Soil nutrient depletion is a common consequence of most African agriculture (Smaling 1993). Improved organic techniques of nutrient supply will undoubtedly contribute to future soil health and productivity, but relying only on nutrient recycling, however efficient, will not generate the food-production increases required in sub-Saharan Africa, nor will restore depleted soils (Janssen 1993). For the foreseeable future, the environmental consequences of continued low use of fertilizers through nutrient mining and increased use of marginal lands are more inevitable and devastating than those anticipated from increased fertilizer use (Dudal and Byrnes 1993).

Mineral fertilizers must be included in any agricultural development strategy with a hope of reversing Africa’s unfavorable food-production trends. As a result of declining real prices over much of the past century, fertilizer has been vital to the rapid increases in world crop production (Tomich, Kilby, and Johnston, 1995). Since the mid-1960s, 50-75% of the crop yield increases in non-African developing countries have been attributed to fertilizers (Viyas 1983). Fertilizers also complement other major inputs and practices (e.g., improved seeds, better water control) that have had the greatest impact on yield (Heisey and Mwang, 1996).

Although there has been some progress in agricultural productivity growth in Sub-Saharan African (SSA) during the past several decades, current productivity growth lags far behind that in other regions of the world and is well below the growth required to meet food security and poverty reduction goals set forth in national and regional plans. A few statistics on cereal production illustrate the point. SSA cereal yields averaged 1.1 tons/ha in 2000 while those in Asia, Latin America, and the Middle East/North Africa averaged 3.7, 2.8, and 2.7 tons, respectively. SSA's average annual growth in cereal yields from 1980–2000 was only 0.7% whereas rates for other regions ranged from 1.2 to 2.3%. Growth in SSA cereal production per capita during this period was stagnant, whereas those in other regions increased from 0.90 to 2.3%. In short, Africa has not yet experienced its "Green Revolution" (Statistics from UN Millennium Project 2005).

Soil scientists are quick to point out that soils in Africa are inherently less fertile than in Asia where the Green Revolution took place (Voortman, Sonneveld, and Keyzer 2000). Low inherent fertility is exacerbated by less favorable climate (low, poorly distributed rainfall and high temperatures). The slow productivity growth is not surprising given SSA's less favorable agro-ecological conditions, plus lower investment in irrigation, and much lower use of fertilizer (Vanlauwe *et al.*, 2002). In every region of the world, the intensification of crop-based agriculture has been associated with a sharp increase in the use of chemical fertilizer. Given the generally low levels of fertilizer use in Africa, there can be little doubt that fertilizer use must increase in Africa if the region is to meet its agricultural growth targets, poverty reduction goals, and environmental sustainability objectives (Morris *et al.*, 2007).

Low fertilizer use is one of the factors explaining lagging agricultural productivity growth in Africa. In 2002, the average intensity of fertilizer use in Sub-Saharan Africa was only 8 kilograms per hectare of cultivated land, much lower than in other developing regions. Even when countries and crops in similar agroecological zones are compared, the rate of fertilizer use is much lower in Africa than in other developing regions, and crop yields are correspondingly lower (Morris *et al.*, 2007). African soils present inherent difficulties for agriculture, and land-use practices during the past several decades have exacerbated those difficulties through nutrient mining by crops, leaching, and inadequate erosion control. Africa's land degradation problems can be attributed to many causes, but analysts generally agree that a fundamental contributing factor has been the failure by most farmers to intensify agricultural production in a manner that maintains soil fertility (Morris *et al.,* 2007).

(ii) N-Fertilizer application

Roy *et al.* (2006) recommended split application of N-fertilizer. They said: "When part of the total N is applied to young plants at the beginning followed by one or two supplementary N applications according to requirements, it results in higher distribution and labour costs. However, the N reserves of the soil are better utilized, transient deficiencies are avoided, and fertilization can be better adjusted to crop needs. The number of portions (splits) in which the total amount of N is to be applied depends on several factors".

Alberta (2002) found that placement with or very near the seed is not necessary to ensure effective utilization as nitrogen fertilizers are very soluble and move readily in moist soil. According to the study, placement options that can be considered include: broadcast, pre-plant band, side-band or mid-row band at planting, and seed row placement. Jones and Jacobsen (2001) found that large differences in yield and quality are generally not expected to be influenced by varying N fertilizer placement methods because nitrate is mobile in soils. However, semi-arid conditions increase the likelihood that placement may affect yield because nutrient mobility decreases with lower soil water content.

P-Fertilizer application

Research conducted by Roy *et al.* (2006) achieved the following results: Localized placement of phosphorus fertilizers might include row, band, or strip placement. It is generally presumed that a localized or band application reduces fertilizer contact with the soil thereby resulting in less phosphorus sorption and precipitation reactions and, thus, enhanced availability to crops. However, for soils with a high phosphorus-fixing capacity, where phosphorus is relatively immobile, placement of the fertilizer where root contact is enhanced may be an equally or more important mechanism than restricting fixation. Jones and Jacobsen (2001) found that P should be applied immediately before or at planting due to its immobility in soil. Besides they noticed that top dressing of P is not expected to affect crop yields because the P would likely become bound near the soil surface and not migrate to the actively growing root system.

Alberta's (2002) research led to the following findings. Phosphate fertilizers do not move readily in soil-Placing the band of phosphate near developing seedling roots of annual crops is most effective-Placement below the depth of seeding may improve availability under dry conditions because the fertilizer is in a moist part of the root zone for a longer period of time than with seed row placement-Broadcast-incorporated applications are less effective than when fertilizer is banded with or near the seed of annual crops- Broadcast application should be two to four times the recommended rates for banding or seed row application.

Roy *et al.*(2006) focused their research on annual crops and found that overwhelming evidence indicates that phosphorus fertilizers should largely be applied pre-plant. Also he noticed that phosphorus moves to plant roots primarily by diffusion, and young seedlings of most annual crops are very sensitive to phosphorus deficits. Furthermore, yields of some crops often fail to recover fully from transitory phosphorus deficits. Alberta (2002) focused his research on established forages and found that response to broadcast applications may be delayed owing to the slow movement of phosphorus into the root zone. The results showed that a greater response may occur in the year following application than in the year of application. In case of a soil that is very deficient in phosphorus, he recommended to band or incorporate phosphate before seeding perennial forages. The research results of Jones Jacobsen (2009) showed that P placement is expected to cause larger effects on P availability and crop yield because unlike N, P is relatively immobile in the soil.

K-Fertilizer application

Alberta (2002) found that potassium moves in the soil more readily than phosphorus, but for annual crops, potassium fertilizers are more efficient when drilled with the seed or banded. He noticed that broadcast applications can be used at about twice the rate used for drill-in application. Jones and Jacobsen (2009) found that effects of K placement are expected to be more than with N and less than with P as the mobility of K is intermediate between N and P. Therefore, starter K, either broadcast, banded, or placed with the seed, has been shown to increase yields.

Roy *et al.* (2006) found that the movement of K^+ by diffusion towards the roots is more rapid when the concentration of K^+ in the soil solution has been increased and this explains why K fertilizer placement in close proximity to the crop roots often results in increased K uptake efficiency. Therefore, K placement may help to 'protect' fertilizer K from being adsorbed or 'fixed' and rendered unavailable to crop plants by clay minerals. Jones and Jacobsen (2009) reminded that the efficient placement, splitting and timing of K fertilizers in coarse-textured, sandy or highly weathered tropical soils with a small cation exchange capacity can help to reduce leaching losses and increase fertilizer recovery efficiency (RE).

2.1.2 Nutrient Use Efficiency (NUE)

Given scarcities of suitable agricultural land in several developing countries, there is no escape from the necessity for a good part of the required production increases to come by extracting more output from each hectare cultivated. That is, agriculture will be becoming ever more intensive. Obviously, what is required is intensification that can keep threats to the resource base and the wider environment within bounds not threatening the sustainability of the system. This indicator shows the potential environmental pressure from inappropriate fertilizer application (Roberts, 2008). Intensive fertilizer application is linked to nutrient losses that may lead to eutrophication of water bodies, soil acidification, and potential of contamination of water supply with nitrates. The actual environmental effects will depend on the adoption of nutrient losses reducing commensurate with soil conditions and crop yields under prevailing meteorological conditions (Roberts, 2008).

Awareness of and interest in improved nutrient use efficiency has never been greater. Driven by a growing public belief that crop nutrients are excessive in the environment and farmer concerns about rising fertilizer prices and stagnant crop prices, the fertilizer industry is under increasing pressure to improve nutrient use efficiency. However, efficiency can be defined in many ways and is easily misunderstood and misrepresented. Definitions differ, depending on the perspective. Environmental nutrient use efficiency can be quite different than agronomic or economic efficiency and maximizing efficiency may not always be advisable or effective (Roberts, 2008).

Agronomic efficiency may be defined as the nutrients accumulated in the above-ground part of the plant or the nutrients recovered within the entire soil-crop-root system. Economic efficiency occurs when farm income is maximized from proper use of nutrient inputs, but it is not easily predicted or always achieved because future yield increases, nutrient costs, and crop prices are not known in advance of the growing season. Environmental efficiency is site-specific and can only be determined by studying local targets vulnerable to nutrient impact (Roberts, 2008).

Nutrients not used by the crop are at risk of loss to the environment, but the susceptibility of loss varies with the nutrient, soil and climatic conditions, and landscape. In general, nutrient loss to the environment is only a concern when fertilizers or manures are applied at rates above agronomic need. Though perspectives vary, agronomic nutrient use efficiency is the basis for economic and environmental efficiency. As agronomic efficiency improves, economic and environmental efficiency will also benefit (Roberts, 2008).

Optimizing nutrient use efficiency

The fertilizer industry supports applying nutrients at the right rate, right time, and in the right place as a best management practice (BMP) for achieving optimum nutrient efficiency (Roberts, 2008).

Right rate: Most crops are location and season specific depending on cultivar, management practices, climate, etc., and so it is critical that realistic yield goals are established and that nutrients are applied to meet the target yield. Over- or under-application will result in reduced nutrient use efficiency or losses in yield and crop quality. Soil testing remains one of the most powerful tools available for determining the nutrient supplying capacity of the soil, but to be useful for making appropriate fertilizer recommendations good calibration data is also necessary. Unfortunately, soil testing is not available in all regions of the world because reliable laboratories using methodology appropriate to local soils and crops are inaccessible or calibration data relevant to current cropping systems and yields are lacking. Other techniques, such as omission plots, are proving useful in determining the amount of fertilizer required for attaining a yield target (Witt and Doberman, 2002).

Right time: greater synchrony between crop demand and nutrient supply is necessary to improve nutrient use efficiency, especially for N. Split applications of N during the growing season, rather than a single, large application prior to planting, are known to be effective in increasing N use efficiency (Cassman *et al*., 2002). Tissue testing is a well known method used to assess N status of growing crops, but other diagnostic tools are also available. Chlorophyll meters have proven useful in fine-tuning in season N management (Francis and Piekielek, 1999) and leaf color charts have been highly successful in guiding split N applications in rice and now maize production in Asia (Witt *et al*., 2005). Precision farming technologies have introduced, and now commercialized, on-the-go N sensors that can be coupled with variable rate fertilizer applicators to automatically correct crop N deficiencies on a site-specific basis. Another approach to synchronize release of N from fertilizers with crop need is the use of N stabilizers and controlled release fertilizers. Nitrogen stabilizers (e.g., nitrapyrin, DCD [dicyandiamide], NBPT [n-butylthiophosphoric triamide]) inhibit nitrification or urease activity, thereby slowing the conversion of the fertilizer to nitrate (Havlin *et al.*, 2005). When soil and environmental conditions are favorable for nitrate losses, treatment with a stabilizer will often increase fertilizer N efficiency. Controlled-release fertilizers can be grouped into compounds of low solubility and coated watersoluble fertilizers. Most slow-release fertilizers are more expensive than water-soluble N fertilizers and have traditionally been used for high-value horticultural crops and turf grass. However, technological improvements have reduced manufacturing costs where controlled-release fertilizers are available for use in corn, wheat, and other commodity grains (Blaylock *et al*., 2005).

Right place: application method has always been critical in ensuring fertilizer nutrients are used efficiently. Determining the right placement is as important as determining the right application rate. Numerous placements are available, but most generally involve surface or sub-surface applications before or after planting. Prior to planting, nutrients can be broadcast (i.e. applied uniformly on the soil surface and may or may not be incorporated), applied as a band on the surface, or applied as a subsurface band, usually 5 to 20 cm deep. Applied at planting, nutrients can be banded with the seed, below the seed, or below and to the side of the seed. After planting, application is usually restricted to N and placement can be as a top dress or a subsurface sidedress. In general, nutrient recovery efficiency tends to be higher with banded applications because less contact with the soil lessens the opportunity for nutrient loss due to leaching or fixation reactions. Placement decisions depend on the crop and soil conditions, which interact to influence nutrient uptake and availability (Roberts, 2008).

Plant nutrients rarely work in isolation. Interactions among nutrients are important because a deficiency of one restricts the uptake and use of another. Numerous studies have demonstrated that interaction between N and other nutrients, primarily P and K, impact crop yields and N efficiency. For example, data from a large number of multi-location on-farm field experiments conducted in India show the importance of balanced fertilization in increasing crop yield and improving N efficiency (Roberts, 2008). Adequate and balanced application of fertilizer nutrients is one of the most common practices for improving the efficiency of N fertilizer and is equally effective in both developing and developed countries. In a recent review based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, P, and K increased first-year recoveries an average of 54% compared to recoveries of only 21% where N was applied alone (Fixen *et al.,* 2005).

Efficiency and effectiveness

Improving nutrient efficiency is an appropriate goal for all involved in agriculture, and the fertilizer industry, with the help of scientists and agronomists, is helping farmers work towards that end. However, effectiveness cannot be sacrificed for the sake of efficiency. Much higher nutrient efficiencies could be achieved simply by sacrificing yield, but that would not be economically effective or viable for the farmer, or the environment. This relationship between yield, nutrient efficiency, and the environment was ably described by Dibb (2000) using a theoretical example. For a typical yield response curve, the lower part of the curve is characterized by very low yields, because few nutrients are available or applied, but very high efficiency. Nutrient use efficiency is high at a low yield level, because any small amount of nutrient applied could give a large yield response. If nutrient use efficiency were the only goal, it would be achieved here in the lower part of the yield curve. However, environmental concerns would be significant because poor crop growth means less surface residues to protect the land from wind and water erosion and less root growth to build soil organic matter. As you move up the response curve, yields continue to increase, albeit at a slower rate, and nutrient use efficiency typically declines.

The relationship between efficiency and effectiveness was further explained when Fixen (2006) suggested that the value of improving nutrient use efficiency is dependent on the effectiveness in meeting the objectives of nutrient use, objectives such as providing economical optimum nourishment to the crop, minimizing nutrient losses from the field, and contributions to system sustainability through soil fertility or other soil quality components.

2.1.3 Combined application of organic and mineral inputs

Organic inputs contain nutrients that are released at a rate determined in part by their chemical characteristics or organic resource quality. However, organic inputs applied at low rates commonly used by smallholder farmers in Africa seldom release insufficient nutrients for optimum crop yield. Combining organic and mineral inputs has been advocated as a sound management principle for smallholder farming in the tropics because neither of the two inputs is usually available in sufficient quantities and because both inputs are needed in the long-term to sustain soil fertility and crop production (Vanlauwe and Zingore, 2011).

Giller (2002) realized that it is important to combine mineral and organic sources of nutrients to get the full advantages of both sources. Vanlauwe *et al.* (2001), indicated that combining mineral fertilizer with organic inputs can substantially improve agronomic efficiency of the nutrients compared to the same amount of nutrients applied through either source alone.

Cadisch *et al.* (1997) found that combined application results in improved agronomic efficiency for a number of reasons. First, common mineral fertilizers lack the minor nutrients essential for crop growth, organic resource contain these, but to meet the crop's major nutrient requirements (N, P and K), often excessive application rates (more than ten tons of dry matter per hectare) are required if those organics are the only input and use efficiency of nutrients applied through organic materials alone is often low. Second, a combination of mineral and organic sources results in a general improvement in soil fertility status (Okalebo *et al.* 2003). Nziguheba *et al.* (2000) proved that an increase in soil organic matter content enables improved nutrient retention, turnover and availability; particularly P availability is enhanced by organic residue application. Organic amendments also counteract soil acidity and Al toxicity (Pypers, *et al.*, 2005). Hudson (1994) concluded that soil structure is improved, soil erosion is reduced, water infiltration and storage become better and root development is improved through organic amendment application.

2.2 Production and utilization of Irish potato

Irish potato, *Solanum tuberosum* L., was introduced into Europe from the Andes in the 16th Century from where it spread to Africa in the 19th Century through the activities of European missionaries, and it remained an elitist food for some time. The introduction of potato in Central Europe started by Spain, moved through Italy and then reached Germany; it was accelerated by the problems of the hunger (famine) resulting from the Second World War. The potato was introduced into other parts of the World by missionaries and colonial political powers of Europe. It is within this framework that North America received this crop coming from England; British church men brought Irish potato to many parts of Asia. It reached China around the years 1700 coming from Indonesia. Irish potato had firstly been introduced in North Africa due to its proximity to Europe. Many African governments have encouraged the production of potato such that the crop is an important commodity of internal trade (Ochigbo *et al*., 1989).

In Rwanda, the potato was introduced around 1904 by Germans and its official introduction took place in 1930 by the Belgian administrators. Irish Potato found favorable soils especially in areas of high altitude. In the beginning Irish potato was considered as a food of the Belgian colonialists and was integrated only very slowly in the traditional agricultural systems (MINAGRI, 2009).

2.2.1 Importance of Irish potato

Importance of Irish potato in the world

Irish Potato occupies the fourth place after rice, wheat and corn in the world and it is the only tuber produced in high altitudes where it generates income to producers. Irish potato has an economic advantage compared to other crops. This is why it is widespread in the world. Indeed it is a culture having a relatively short vegetative cycle. It is also a cash crop due to its relatively high yield. Irish potato does well in cold areas with heavy rains where conditions are not appropriate for other tubers (Ochigbo *et al*., 1989).

Importance of Irish potato in Rwanda

Irish potato plays a significant role in the nutrition of Rwandan population, both urban and rural. The potato is concentrated in the zone of high altitudes. This zone has a surface area of 574.450 ha (around 22% of the national agricultural surface).This zone produces 95 % of Irish potato nationally, the remainder being produced on the areas where this crop is less adapted. The importance of this crop is shown on the one hand, by the fast growth of its production during the last few years and by the evolution of its consumption and marketing on the other hand.The production of Irish potato was for a long time low until the creation of ISAR in 1962. Rwanda's main food crops in terms of production are banana (62.5%), sweet potatoes (17.9%), cassava (4.5%), Irish potatoes (4.3%), pulse (beans and pea, 3.9%), sorghum (2.9%), maize (1.4%), and the rest are paddy, wheat, soybean and groundnuts (MINAGRI, 2009).

2.2.2 Irish potato production

(i) Time of planting

The time of planting depends on the onset of rains, planting should commence at least 1-2 weeks after the onset of the steady rains. Late planting should be avoided as the crop tends to come into full flush during the peak of blight incidence (Ochigbo *et al.*, 1989).

(ii) Type of soil

Potato is suited for a wide variety of soil type. An ideal potato soil is deep, well drained, has silt loam or a sandy loam texture and is slightly acidic. Such soils can store a large amount of water without becoming saturated or muddy. They are easy to work and they respond to good management. However, any soil will become unproductive under bad management. Therefore, regardless of soil type, it is necessary to maintain soil fertility, keep good soil structure and control erosion (Ochigbo *et al.*, 1989).

(iii) **Rotation**

Potato should be grown in rotation with other crops. It is not advised to grow potato on the same soil of which potato or other solanaceous (tomato, pepper, garden eggs, etc.,) were grown during the two previous years so as to reduce incidence of soil-borne diseases such as bacterial wilt and nematodes (Ochigbo *et al*., 1989).

(iv) Land preparation

Soil tillage, seedbed preparation and ridging will be done in such a way that quick emergence, deep root penetration and good drainage are insured. Potato has a weak root system and impermeable layers in the soil impede water and nutrient uptake and reduce yield. Good land preparation can be achieved by the use of the hoe or tractor-drawn implement. Efforts must be made to break clods as they interfere with potato emergence and root development. Good soil preparation minimizes initial weed problems. Ridges should be prepared (75-90cm) as soon as the rains begin. In the case of dry seasons, irrigation ridges should be prepared when the soil is moist. If beds are used, care should be exercised to ensure that tubers are not exposed to avoid greening (Ochigbo *et al*., 1989).

(v) Seeding rate and seed size

Potato yields are proportional to seed size up to a point. Very small or extremely large tubers should therefore not be used for planting. The recommended seed sizes are those between 35-50mm or 30-60g. Spacing should vary according to varieties and ecological conditions. But 70cm between rows and 30cm between crops is considered as reference. This is equivalent to 47619 plants/ha. Plant one seed-tuber per hole. Planting depth should be about 10cm. Deep planting or too shallow planting should be avoided (Ochigbo *et al.,* 1989).

(vi) Fertilizer application

Nutrient demands of potato, like other tuber/root crops, are high. Highest uptake of nitrogen, phosphorus and potassium occurs during early stages of Irish potato development. Old roots do not readily absorb nutrients. Application can be done by broadcasting, banding or placement (Ochigbo *et al.,* 1989).

Organic manure: the manure acts not only ordinarily like manure but also like an amendment; it improves the structure of the soil, its ventilation and its water holding capacity. It generally causes a light decrease of dry matter content in the tubers (Ochigbo *et al.,* 1989).

Mineral fertilizer: nitrogen is used to build proteins and for the development and the vegetative growth of the plant. It plays a significant role in the production and maintenance of an optimum plant canopy for continue tuber growth throught the growing season. Deficiencies can reduce yields, cause yellowing of the leaves and stunt growth (Babaji *et al.,* 2009). Phosphorus is used to build proteins as the nitrogen, it is also necessary for the growth of young plants, the development of the roots and the formation of the tubers. It is also important for early root development and tuber formation. Deficiency symptoms are purple stems and leaves; maturity and growth are retarded, yields of fruit and flowers are poor, premature drop of fruits and flowers may often occur. Lack of phosphorus involves a reduction in yield (Babaji *et al.,* 2009). Potassium generally acts in the same direction with nitrogen and contributes to accentuate its effect. It stimulates early haulms growth and vigour as well as increases tuber size and yield. . Deficiencies result in low yields, mottled, spotted or curled leaves, scorched or burned look to leaves (Babaji *et al.,* 2009). For instance, in Rwanda the ISAR recommended rates are defined as follows: the application of 100-400 kg/are (10-40 t/ha) of well broken up manure or compost at ploughing time and 3 kg/are (0.3 t/ha) of N. P. K (17-17-17) at the planting time .

(vii) Weed control

One weeding is sufficient but it must be done very early, not later than four weeks after planting. Later weeding may result in extensive damage to the root system, especially where hand hoeing is used and could lead to yield losses (Ochigbo *et al*., 1989).

(viii) Pest and disease control

The most important diseases are caused by fungi, bacteria and viruses. The most important pests are nematodes, termites, mealy bugs and millipedes. IPM (Integrated Pest Management) is found to be the best approach for diseases and pests control (Ochigbo *et al.,* 1989).

(ix) Harvesting

The vegetative cycle varies from 90 to 140 days depending on the varieties and climatic conditions. The potato can be harvested at complete maturity if it is intended for a long conservation and export or before complete maturity if it is intended for an immediate marketing. The maturity of tubers is indicated by senesceing (drying and yellowing) of stems and leaves, the fact that the tubers can easily be separated from stolons (Ochigbo *et al.,* 1989). It is recommended to cut stems (killing haulms) at the level of the soil 2-4 weeks before harvest to stimulate the hardening of the skin of tubers or to hasten tuber skin setting. Harvesting should be avoided immediately after a heavy rain. Soil must not be too wet to avoid carrying wet soil and tubers to the store. Harvested tubers are removed from the field immediately after harvest to avoid exposing them to the sun. Exposure to the sun would result in extensive damage to the tubers (sun scald and other rots in store) (Ochigbo *et al.,* 1989). Under temperate and subtropical conditions, an irrigated crop of about 120 days can yield from 25 to 35 tones/ha of fresh tubers, while farmers in the tropics can harvest between 15 and 25 tones within 90 days of planting (FAO, 2006).

2.2.3 Irish potato fertilization guidelines

Fertilizer application should be timed to crop needs and development stage, when appropriate through split application. The application should preferably be made by methods that minimize losses and maximize utilization (Maene, 2000).

Roy *et al.* (2006) formulated the following recommendations:

1. Concerning N-fertilizers, split application is better. He advised to apply about two-thirds of the nitrogen recommendation in the seedbed and the remainder top-dressed shortly after emergence if top dressing is planned for management reasons or to reduce the risk of leaching for crops grown on light sand and shallow soils. Different methods of fertilizer application can be adopted according to soil, weather and cultural practices conditions,
2. For P-fertilizer, he recommended the application of total amount at ploughing or planting using special methods of application such as placement or band spreading,
3. Regarding K-fertilizer, the author recommended split application (in case of soil with potential leaching): a half at planting and another one a bit later. Placement method of application was advised.

Lang *et al. (*1999) formulated the following recommendations:

1. Applying a major portion of total seasonal K fertilizer prior to planting has been found effective in obtaining maximum yields. Also they noticed that the practice of applying potassium in multiple split applications provide the advantage of reducing the amount of potassium at planting, thereby reducing the potential for salt concentrations becoming a problem,
2. Nitrogen applications which are split between pre-plant and in-season provide opportunities to increase nitrogen use efficiency and minimize leaching by preventing excess availability. Excessive amounts of nitrogen at planting can elevate salt levels, adversely influencing moisture availability in the zone of new root growth. Avoiding excess nitrogen availability during growth stages I and II also favors a balanced proportion of roots and shoots, resulting in enhanced tuber set,

3. For maximum tuber yields, P should be mixed into the seed bed prior to planting to support: early shoot and root growth (stage I), tuber initiation (stage II), and tuber bulking (stage III). Plant P levels in mid- and late-season (stages III and IV) may be raised by applications of phosphorus using foliar sprays, application through irrigation water, or soil applied phosphorus followed by irrigation. However, due to the small distances phosphorus moves in the soil, feeder roots must be near the soil surface to make in-season application effective.

Regarding methods of inorganic fertilizer application Mahmood *et al*. (2002) did a research whose objective was to compare the different methods of fertilizer application vz broadcasting, placement and banding in Islamabad (Pakistan). The results indicated that the highest yield (18.56 t ha^{-1} in autumn 1988 and 15.67 t ha^{-1} in autumn 1989) was recorded in placement followed by banding (15.94 t ha^{-1} in autumn 1988 and 13.9 t ha^{-1} in autumn 1989) and lowest in broadcasting (12.22 t ha^{-1} in autumn 1988 and 11.56 t ha^{-1} in autumn 1989) treatments. Using banding and placement methods of fertilizer application, 20.24 and 35.55% increase in potato yield was recorded over broadcasting of fertilizer, respectively. A significant difference was found in the three methods of fertilizer application. The doses used were N-P-K 250-125-125 kg ha^{-1}. The results showed the same trend in terms of soil coverage; it was maximum for placement (89.75%), followed by banding (85.50%) and minimum for broadcasting (75.25%).

Hochmuth and Hanlon (2000) conducted a research in Florida with the purpose of reviewing and summarizing potato fertilization research in Florida. The research focused on potato best management practices limited to three macronutrients, N-P-K. For N, they recommended to use a target seasonal N amount of 200 lb/acre (224 kg/ha) to be modified if needed based on leaching rain or leaf-tissue testing before approximately 40 days after planting. They also added that pre-plant N fertilizer is not needed. The same authors suggested to plant potatoes without soluble N fertilizer or only with N that might come with the starter P (ammonium phosphates) fertilizer and to hold N to less than 20 lb/acre (22.40 kg/ha) at planting. They also recommended that using controlled-release N fertilizer (CRF) mixtures with various release patterns could save 25% of the recommended N rate of 200 lb/acre (224 kg/ha). If not using CRF, they suggested to make the first application of N (up to 67%) at cracking (about 14 days after planting) or planting and to apply remaining N within 40 days after planting. The same authors pointed out the necessity to apply 30 lb/acre N in addition to the second N application after any leaching rain occurred just prior to the second application.

Regarding P, Hochmuth and Hanlon (2000) recommended using the Mehlich-1 soil test to determine P needs and following the recommendations for amounts of P fertilizer. They said that high P testing soils do not require P fertilizer and reported that, given cool planting condition (January), there might be a response to a small amount of P added as a starter fertilizer to encourage young root growth. The same authors suggested that required P fertilizer should be banded near the seed piece at planting time and not broadcast before planting.

Concerning K, Hochmuth and Hanlon (2000) reported that potato yield responses to K fertilization from experiments appeared to level off after 100 lb/acre (112 kg/ha) K_2O. The authors continued by saying, since K leaches in sandy soils, total K application should be split into two applications with some K applied at planting or at cracking. They also confirmed that potato yield did not respond to K source on a soil testing medium in M-1 K and pointed out that reduction in the specific gravity of potatoes, or decreased chipping quality, frequently resulted from higher rates of applied K. The authors noted that the application timing of mobile nutrients, such as N or K, was important for greatest yields and also suggested that N fertilizer can be withheld until plant emergence. Finally, they suggested to apply all N and K fertilizers by 35 to 40 days after planting.

Cumings *et al.*, (1939) conducted research titled “Fertilizer placement for potatoes” with the aim of determining the most advantageous placement in which commercial fertilizers may be applied with respect to the potato seed piece. They came out with the following findings: Placement of the fertilizer in a band immediately under, or above, or mixed with the soil around the seed piece usually resulted in delayed emergence of the sprout above ground and reduction in yield. Fertilizer placed in a band at each side of the row rather consistently produced the most rapid emergence of sprouts, the most vigorous plant growth, and the highest yields of primes as well as total yields. Fertilizer placed in a band 2 inches (5 cm) to each side of and on the lower level of the seed piece most consistently produced relatively high yields, the average of which either equaled or slightly exceeded the average yields of the other side placements both nearer and farther from the seed. This is considered the preferable placement from the practical standpoint- Placement of fertilizer in a band at only one side of the row gave lower yields than a band at each side. Hill placement of fertilizer in short bands at each seed piece or hill gave no indication of advantage over comparable placements in continuous bands along the row, for seed spacing ranging from 12 to 16 inches (30 to 40 cm).

Gathungu *et al.*, (2000) conducted research on effect of source (CAN, ASN and urea), time (early, split and late application), and method (broadcast and placement at 0.05 m from seed crop within the furrow) of nitrogen application on growth and yield components of potato in Kenya, the results achieved showed: the ratio of tuber to the total dry mass content differed significantly among the sources and times of N application at 70 DAE- Number of tubers per plant was not significantly affected by the source of N. However, the time of application of N significantly influenced the number of tubers per plant- The potato tuber yield significantly differed amongst the sources and times of application of N- The method of application and the interaction between the source, time, and method of N application had no significant effect on tuber to total dry mass ratio 70 DAE, number of tubers and tuber yield per plant.

CHAPTER 3

3.0 Materials and methods

3.1 Study sites

Geo- physical characteristics of the study locations

A field trial was established in two sites: site of research station, Kinigi RAB (Rwanda Agricultural Board) station-Musanze District /Northern Province and another one on-farm,Kibeho site/ Nyaruguru District-Southern province. Both sites have an equatorial-continental temperate type of climate classified as AW3, according to the Köppen classification. They have four seasons which are determined by the variability of rainfall (MINIRENA, 2004).

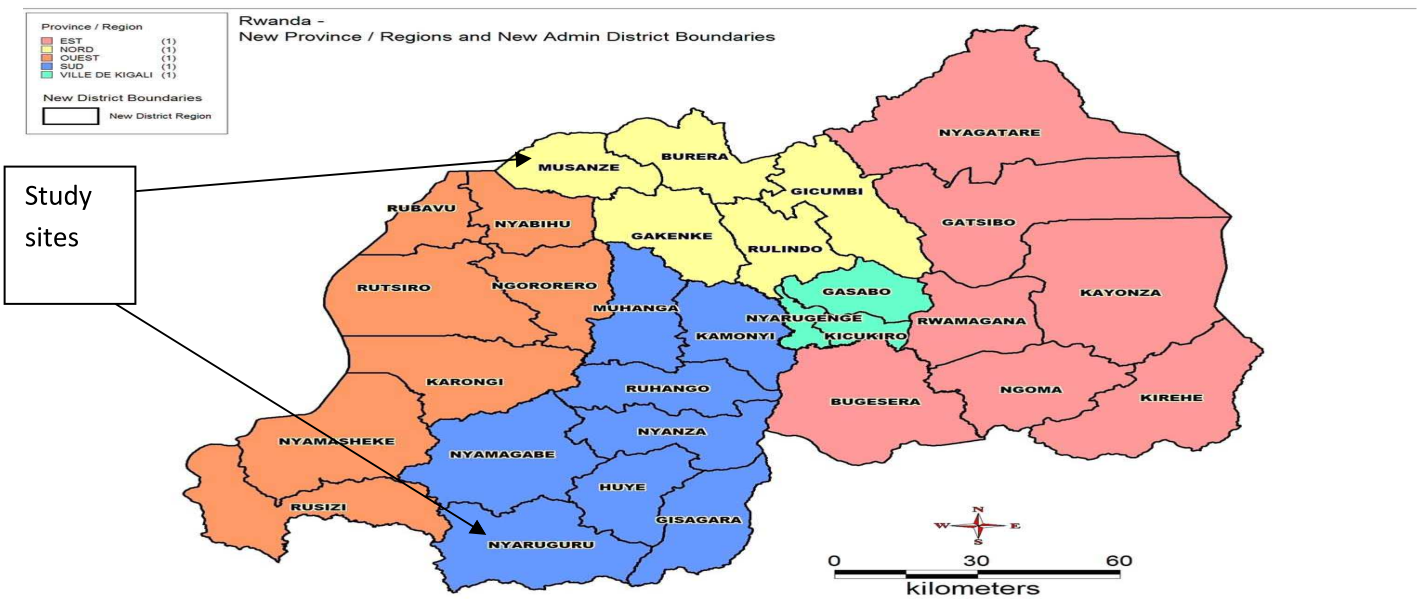

Figure 1: Rwanda Districts map (Musanze/ North Province and Nyaruguru/ South Province, sites of the study)

Kibeho site is located in Nyaruguru District, between latitude 2^{o} 65’S and 29^{o} 55’E and situated at 1894m above sea level. The district of Nyaruguru has got a relief ranging between 1,600 and 1,800 m (above sea level) of altitude. Its average rainfall is around 1,200 mm per annum; its daily temperature average is of more or less 20°C (Rukangantambara and Maniriho, 2012). Kinigi site is located in Musanze District, between latitude 1^{o} 45’S and 29^{o} 56’E and situated at 2200m above sea level. Musanze district is located in a volcanic region. This region is prone to soil erosion due to steep slopes on the southern aspect of the volcanoes and high rainfall. Generally, the north-western region of Rwanda has a moderate and humid climate due to its high altitude and abundant rainfall, which records the national annual rainfall maxima of 2000 mm between 2000 and 3000 m (above sea level) of altitude. There is rainfall throughout the year but with two heavy rainy seasons; the longest being from February to June with a peak in April while the shortest is from September to December with a peak in November. Near the Park (where was located Kinigi site), the main soils are of volcanic origin in the category of Andosols (black in colour) and Andic soils. The volcanic soils developed from volcanic ashes and evolved as a function of climate of the region. The volcanic soils are generally fertile (Hitimana *et al.*, 2006).

Table 1:Selected meteorological data of research sites

	Rainy days		Rainfall (mm)		Monthly temperatures (^{o}c)				Monthly temperatures Range (^{o}c)		Daily temperature (^{o}c)			
Months	Kibeho	Kinigi	Kibeho	Kinigi	G*/Kibeho		Kinigi		G*/Kibeho	Kinigi	Gikingoro(G*) /Kibeho		Kinigi	
					Max	Min	Max	Min			Mean	Range	Mean	Range
March	16	17	253.1	175.3	756.4	446.4	657.4	188.4	310	469	19.4	10	13.6	15.1
April	17	25	175.3	412.1	675	441	569.7	174.5	234	395.2	18.6	7.8	12.4	13.2
May	16	22	253.3	257.4	678.9	443.3	563.6	186.2	235.6	377.4	18.1	7.6	12.1	12.2
June	2	12	41.1	42.1	678	426	559.4	186.3	252	373.1	18.4	8.4	12.4	12.4
July	0	5	0	4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Source: Rwanda meteorological service, Kigali/Rwanda, 2012.

G*:Data collected from Gikongoro meteorological data station (Kibeho nearest station)

N.A: Not available

3.2 Experimental design and treatments

Field trials were established in two sites (site of research station, Kinigi RAB station-Musanze district /Northern Province and another one on-farm, Kibeho site/ Nyaruguru district-Southern province) during the long rainy season of 2012. The experiment was run for four months in the South and four and a half months in the North. The experimental design used was RCBD in a factorial arrangement, with treatments replicated three times. Two factors were considered in the study. The first was mineral fertilizer (N.P.K 17-17-17) application methods with two levels while the second was timing of mineral fertilizer application which was involved in the study under five levels. The experiment had a subtotal of ten treatments per block and a total of thirty treatments. Plots of 3.5×3.0m, with five lines in each, were used as experimental units. Adjacent blocks and plots were separated by guard-rows of 1m. The following table illustrates experimental treatments resulting from combinations of different levels of the two factors under study.

Methods of fertilizer application(F_x)	**Timing of fertilizer application(T_x)**				
	T_1	T_2	T_3	T_4	T_5
F_1	F_1T_1	F_1T_2	F_1T_3	F_1T_4	F_1T_5
F_2	F_2T_1	F_2T_2	F_2T_3	F_2T_4	F_2T_5

Figure 2: Research treatments and combinations of levels of research factors

Factor I: Methods of mineral fertilizer application (F_x), with two levels

(i) F_1: Banding (banding in row)

(ii) F_2: Placement (localized placement)

Factor II: Timing of mineral fertilizer application (T_x), with 5 levels

(i) T_1: 100% of N.P.K fertilizer applied at planting time

(ii) T_2: 50% and 50% of N.P.K fertilizer applied at planting and two weeks after emergence (at weeding time), respectively

(iii) T_3: 75% and 25% of N.P.K fertilizer applied at planting and two weeks after emergence (at weeding time), respectively

(iv) T_4: 50% and 50% of N.P.K fertilizer applied at planting and four weeks after emergence (at earthing up time), respectively

(v) T_5: 75% and 25% of N.P.K fertilizer applied at planting and four weeks after emergence (at earthing up time), respectively

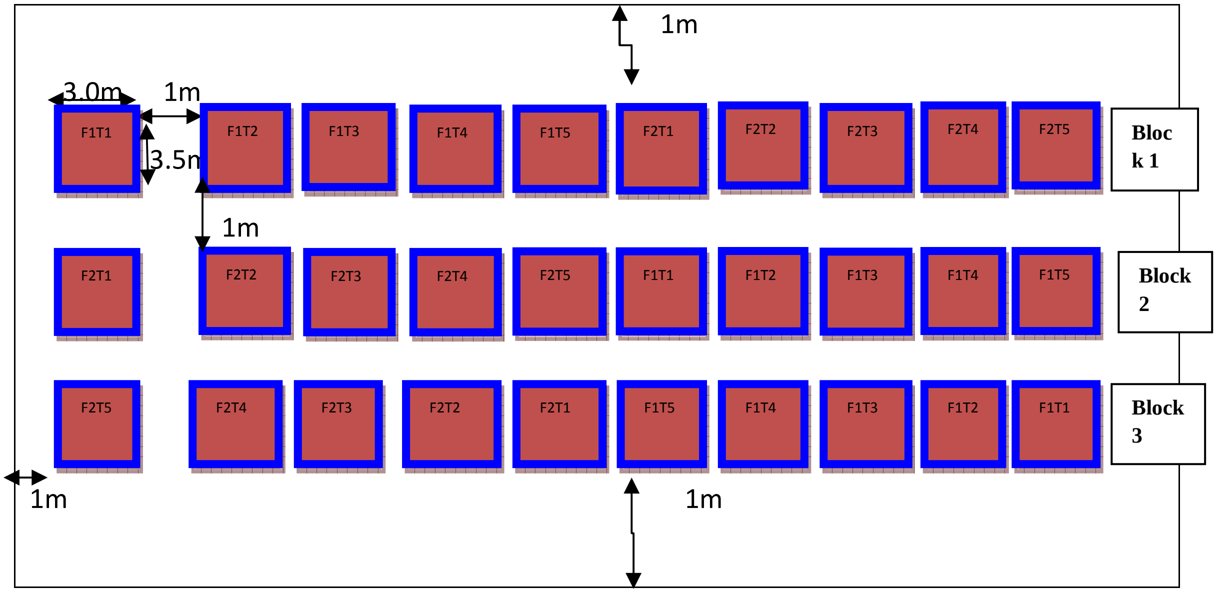

Figure 3: Layout of experimental design

3.3 Agronomic practices

Land preparation: soil tillage, seedbed preparation and ridging were done in such a way that quick emergence, deep root penetration and good drainage were insured.

Seeding rate: one tuber-seed was planted per hole. Recommended spacing of 30×70cm was used; this was equivalent to 47619 plants/ha. Using plots of 3.5×3.0m, with five lines in each, the number of plants per plot was 50. Depth of planting was 10cm.

Fertilizer application: blanket application of well decomposed FYM was broadcast at the recommended rate of 300 kg/are (30 t/ha). FYM was incorporated into the soil with a hoe one week before the tuber-seeds were planted. N-P-K (17-17-17) fertilizer was applied at the recommended rate of 3kg/are (0.3 t/ha), methods and timing of application used are those defined earlier for the levels of the factors under study. Regarding methods of mineral fertilizer application, the N-P-K fertilizer was spreaded along rows of 10cm diameter and within 10cm diameter around the seed or seedling (plant) depending on the period of application, for row banding and localised placement methods, respectively. The seed or seedling was never in direct contact with the fertilizer.

Weeding: one weeding was sufficient, it was executed two weeks after emergence and by hand hoeing.

Ridging (earthing up): one ridging was carried out four weeks after emergence by hand hoeing**.**

Pests and diseases management: IPM approach was adopted, spraying against late and early blight using Dithane M45 (dose of 30g per 15 l) was regularly done (once per week).

3.4 Selected agronomic parameters measurement

Crop performance was evaluated on the basis of many parameters considered as its components. Data on the emergence rate, number of stems (primary shoots) per plant, stem height and canopy cover were obtained from ten plants in the middle three rows of each plot. At maturity, tubers were harvested to determine the number of tubers per plant, tuber grades and total tuber yields. Number of tubers per plant and tuber grades were determined using the same plant samples as the ones used for emergence rate, number of stems per plant and stem height determination while the total yield was obtained by weighing all tubers pulled out from the entire each plot minus the guard rows. The yields were converted into tons/ha.

(i) Emergence rate: physical counting was done 28days after sowing (28DAS) and the parameter was expressed in percent.

(ii) Number of stems (shoots) per plant: counting was done 7, 14, 21, 28 and 35days after emergence (DAE).

(iii) Stem length: measurements were taken 14, 28, 42, 56 and 70 days after emergence (DAE) using a tape.

(iv) Canopy cover: was expressed in percent of row width covered by the crop and it has been measured once using a tape and calculated at the period of 70DAE.

(v) Number of tubers per plant: counted physically after pulling out tubers (at harvesting time).

(vi) Grades of tubers: grading was done after harvesting. Tubers were ranked in three classes. Big size: >60mm diameter-Middle size: 30-60mm diameter- small size: <30mm diameter. Different grades were weighed separately and values recorded were converted into tons per hectare.

(vii) Tuber yields: were wet weighed per plot after gathering tubers from all grades and also converted into tons per hectare.

3.5 Soil sampling

Soil sampling was done on farms where the field trials were conducted. The top 0-30cm soil was dug randomly from the whole farm (before planting) and from each plot (before harvesting).

3.6 Soil chemical and physical characterization

Soil chemical characterization: the composite samples were used for the chemical analysis before setting up the experiment on one hand and before harvesting on the other hand. They were characterised for pH, organic carbon, available phosphorus, exchangeable bases, cation exchange capacity and total nitrogen.

Soil physical characterization: the composite samples were physically characterized for texture and bulk density. Both properties were determined before setting up the experiment. Soil chemical and physical characterisation was done as outlined below.

3.6.1 Determination of soil pH

The pH was determined using the 1:2.5 ratio of soil : water. The air dried samples were passed through a 2mm sieve and used in determination of pH. Six grammes of the sieved samples were weighed and put in two sets of clean plastic bottles. To each set, 15ml of distilled water was added. The samples were shaken for 30 minutes in a reciprocating mechanical shaker, allowed to stand for 30 minutes before reading the pH on pH meter.

3.6.2 Determination of available phosphorus

The Mehlich soil test for P also known as the dilute double acid as developed by Mehlich *et al*. (1953) was used. Soil samples which had been air dried, ground and sieved through 2mm sieve were extracted using 50ml of Mehlich extracting solution (double acid, containing 0.025N H_2S0_4 and 0.05N HCl). The mixtures in shaking bottles were placed on reciprocating shaker and shaken for 30 minutes at 180 rpm at room temperature. The mixtures were then filtered through filter papers, Whatman N^{o} 2. The filtrate was thereafter analysed for P colorimetrically using blank and standards prepared in the Mehlich extracting solution and the absorbence read on a spectrophotometer at 882nm wavelength.

3.6.3 Determination of organic carbon

Organic carbon was determined using the Walkley-Black (1934) oxidation method. This method involves complete oxidation of soil organic carbon using concentrated H_2SO_4 and potassium dichromate. The unused or residual $K_2Cr_2O_7$ is titrated against ferrous ammonium sulphate. The used $K_2Cr_2O_7$ which is the difference between added and residual $K_2Cr_2O_7$ gives a measure of organic carbon content of a particular soil. 0.5g of air dried soil sieved through a 0.5mm sieve was weighed into a set of clean conical flasks. 10ml of 1N $K_2Cr_2O_7$ was added to each and swirled gently. 20ml of 36N H_2SO_4 was rapidly added and allowed to stand. Distilled water was added followed by a drop of mixed indicator. The content was thereafter titrated with 0.5N ammonium ferrous sulphate noting the colour changes at the end point.

3.6.4 Determination of CEC

CEC of the soil samples was determined using Metson method (1961) which uses normal ammonium acetate as the exchange solution at pH 7. The exchange solution leaches out all the cations in a soil. Excess NH_4^+ was removed with an organic solvent (alcohol). A potassium (K^+) salt solution was used to replace and leach out adsorbed NH_4^+. The amount of NH_4^+ released gives the amount of CEC of a soil. The amount of exchangeable K, Ca and Mg in the extract was determined by flame photometry for K and by atomic spectrophotometry for Ca and Mg.

3.6.5 Determination of total Nitrogen

In the determination of total nitrogen, the Kjeldahl (1883) method was used. This is basically the wet oxidation procedure. 1g of 0.5mm-sieved sample was weighed into a clean digestion tube and mixed, catalyst added followed by 8ml 36N H_2SO_4. Samples were digested for 2hours before and titrated against 0.01N HCl and recording the volume used in titration.

3.6.6 Determination of soil texture

Air-dried soil samples were passed through 2mm sieves to get fine earth. 50g of the sieved soil samples were weighed on an electric balance and moistened with distilled water and hydrogen peroxide added in aliquots of 10ml in a fume chamber. Hydrogen peroxide oxidises any organic matter present in the soil. The sample was allowed to stand for one day for the reaction to take place and thereafter dispersed by adding 50ml of calgon (sodium hexametaphosphate) to separate the particles of sand, silt and clay. The mixtures were then transferred into a 1000ml sedimentation tubes and topped up with distilled water to make 1000ml. The samples were stirred to disperse the particles and readings taken using a hydrometer after 45 seconds of stirring. The temperature of the samples at a particular hydrometer reading was also recorded. Percents of sand, silt and clay were determined using the readings. A textural triangle was then used to assign the soil into its textural class.

3.6.7 Calculation of bulk density

Bulk density of soil is usually determined on core samples (core method) which are taken by driving a metal corer into the soil at the desired depth and horizon. The samples are then oven-dried and weighed. The bulk density of soil is inversely related to the porosity of the same soil: the more pore space in a soil the lower the value for bulk density (Campbell and Henshall, 1991).

Bulk density(ϸ)= mass of soil (M_S)/core volume (V_t): $\rho = \frac{M_s}{V_t}$

Where ϸ is soil bulk density, M_S is mass of soil sample (in core) and V_t is internal volume of the core used (Campbell and Henshall, 1991).

Ten core samples (4 cm diameter and 10 cm high) were collected randomly before the start of the experiment for the determination of soil bulk density using the core method as described above.

3.7 Cattle manure analysis

The organic manure used was cattle manure. It was were decomposed and got from one family per site. Air-dried and ground cattle manure samples were sieved through a 2mm sieve and analysed for organic C, N, P, K, Ca and Mg using the method described by Okalebo *et al.* (1993).

3.8 Data analysis

Data collected on agronomic parameters and on soil chemical parameters were subjected to analysis of variance (ANOVA) using Genstat Discovery edition 14^{th}. The treatment effects were tested for significance using F-test at 5%. Duncan Multiple Range Test (P=0.05) was used for mean separation. Analysis of correlation coefficients, at 5% level of significance, was done to determine the relationship between tuber yields and some other agronomic parameters (stem height, canopy cover and number of tubers per plant).

CHAPTER 4

4.0 Results and discussion

4.1 Effect of timing and methods of N-P-K (17-17-17) application on selected soil chemical properties

The textural class of Kinigi soil is sandy loam with pH 5.7. The soil is low in exchangeable bases (Ca, Mg and K), available phosphorus; medium in organic carbon, total nitrogen, cation exchange capacity (CEC) and soil reaction (pH). The soil bulk density is 1.55 and is in the range of ideal bulk densities to permit effective crop roots growth (Table 2)(Landon, 1991).

Table 2: Selected chemical and physical properties of the experimental sites and organic manure before planting

Materials	C[1]	N[2]	P[3]	Exchangeable bases			CEC	pH	Sand	Silt	Clay	Textural class	Bulk density
	(%)		(ppm)	(meq+/100g Soil)				(1:2.5 soil/ Water)		(%)			(g /cm^3)
Soil				K	Ca	Mg							
Kibeho	5.32	0.45	10.64	0.21	3.86	1.27	15.30	5.8	10	52	38	Slity Clay Loam	1.42
Kinigi	7.80	0.54	10.41	0.20	2.68	0.48	14.30	5.7	59	22	19	Sandy Loam	1.55
Manure	**C**	**N**	**P**	**K**	**Ca**	**Mg**	**C:N**	**Key observation**					
				(%)									
Kibeho	11.50	1.30	0.60	2.15	1.030	0.65	8.85	The low C: N (<<20) ratio indicates that manures are of good quality and ready for immediate and quick decomposition resulting in net mineralization, plant nutrient supply and soil fertility improvement. Immobilization is not predictable in this case.					
Kinigi	12.60	1.41	0.55	2.00	1.042	0.53	9.00						

The textural class of Kibeho soil is silty clay loam with pH 5.8. The soil is low in available phosphorus, exchangeable bases Ca and K but medium in Mg, organic carbon, nitrogen, cation exchange capacity (CEC) and soil reaction (pH). The soil bulk density is 1.42 and is a bit above the superior limit of bulk densities range to enable effective crop roots growth (Landon, 1991). The soil fertility, at both sites, is low for crop production in general, and especially for Irish potato potential performance in particular. Majority of parameters' values analyzed are less than critical values except pH (5.7 and 5.8 at Kinigi and Kibeho sites, rspectively) and Kinigi soil

[1] C: organic carbon
[2] N: total nitrogen
[3] P: available phosphorus (by Mehlich/ dilute double acid)

textural class; so there is need for soil amendment. The application of different fertilizers was expected to benefit the crop and soil. The soil analysis results are in agreement with the findings of many researchers who focused their research works on tropical soil organic matter content and demonstrated how it is poor. Solomon et *al*. (2001) declared that many tropical soils are poor in nutrients and rely on the recycling of nutrients from soil organic matter (SOM) to maintain crop productivity.

According to Katyal et *al.* (2001), agricultural intensification of an area, through clearing and clean cultivation of soils for annual cropping, almost universally causes a decline in soil organic content. Chemical soil properties contributed by SOM that are altered include mineralization of nutrients and their availability to plants, cation exchange capacity, and binding of heavy metals and pesticides. With the amount of SOM reduced there is a need to supplement the soil with additional nutrients in the form of fertilizers. Römkens et *al.* (1999), Six and Paustian (1999) and Six et *al.* (2002) found that due to population growth and small farming unit in the highlands, intensive cultivation of the landscape is becoming more serious cause of natural resource degradation. As a result of high pressure caused by human interference on natural forest and grazing land, soil organic matter (SOM) has declined to low level especially in cultivated soils of the highlands. Consequence of this decreased SOM content resulting in low productivity of agricultural soil due to loss of nutrients through crop removal and run off water erosion.

The low C: N ratio of the manures used indicates that they were of good quality and ready for immediate and quick decomposition resulting in net mineralization. This is in agrrement with the findings of USDA NRCS (1977) stipulating that the carbon:nitrogen ratio (C:N) is used as an indicator of which step in the nitrogen cycle occurs next. Ratios less than 20 mean that excess N is present and nitrification proceeds (with a net gain of N). With ratios between 20 and 30, nitrification and immobilization rates are in equilibrium and there is no net gain or loss of N. With a ratio greater than 30, N is limited and net immobilization occurs with uptake (or loss) of N from the active N cycle (USDA NRCS, 1977). When N is limited at high C:N ratios, nitrogen-fixation by free-living nitrogen fixers is stimulated. Everything else being equal, materials added to the soil with a C:N ratio greater than 24:1 will result in a temporary nitrogen deficit (immobilization), and those with a C:N ratio less than 24:1 will result in a temporary nitrogen surplus (mineralization) (USDA NRCS, 1977).

Data of tables 3 and 4 show the effect of timing and methods of N.P.K (17-17-17) fertilizer application on selected soil chemical properties at Kibeho and Kinigi sites, respectively. At both sites, the effects of methods and timing of N-P-K application on selected soil chemical properties were almost similar. The main effects of methods and timing of the fertilizer application on selected soil chemical properties were not significant ($p \geq 0.05$). The interaction between methods and timing of the fertilizer application did not significantly affect selected soil chemical properties. However, both factors, in combination with blanket FYM application, improved soil nutrient concentrations. The effects of application of FYM (farm yard manure) and N-P-K fertilizer improved soil reaction, organic carbon, total nitrogen, available phosphorus, exchangeable bases (potassium, calcium and magnesium) and CEC, but not significantly ($p \geq 0.05$) (Appendices 18-25). Application of FYM (farm yard manure) and N-P-K fertilizer improved the nutrients status presumably due to the supplied plant nutrients from the materials (Eaton, 2001; Agele *et al.*, 2006).

Improvement in soil nutrient status by farmyard in combination with N-P-K implies that their combination could be used for soil management for sustainable production of Irish potato. Soil organic carbon increased because of FYM applied before planting. The increase in the levels of soil organic carbon (and even organic matter) was expected, since, organic manures have the ability of increasing soil organic matter content (Ojeniyi, 2000). Nutrient availability from organic sources is due to microbial action and improved physical condition of soil (Sarker *et al*. 2004). It has also been reported that the contents of some major nutrients in the soil were slightly dependable on the level of organic matter (Adeniyan and Ojeniyi, 2005).

Table 3:Effect of timing and methods of N-P-K (17-17-17) fertilizer application on selected soil chemical properties at Kibeho site

	pH			C[4]			N[5]			P[6]			K^+			Ca^{2+}			Mg^{2+}			CEC		
Methods / Times	F1[7]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[8]	5.72	5.72	5.72	6.43	6.57	6.50	0.58	0.60	0.59	11.52	11.50	11.51	0.39	0.40	0.39	3.89	4.00	3.94	1.98	1.99	1.98	16.27	16.64	16.45
T2	5.88	5.95	5.91	7.20	7.50	7.35	0.63	0.65	0.64	11.68	11.85	11.76	0.42	0.44	0.43	4.26	4.44	4.35	2.02	2.07	2.04	18.07	19.21	18.64
T3	5.83	5.94	5.89	7.24	7.54	7.39	0.62	0.65	0.63	11.66	11.79	11.72	0.41	0.43	0.42	4.18	4.29	4.24	2.00	2.05	2.02	18.30	19.49	18.89
T4	5.85	5.95	5.90	6.77	7.35	7.06	0.61	0.65	0.63	11.67	11.74	11.70	0.42	0.44	0.43	4.21	4.37	4.29	2.02	2.06	2.04	17.05	19.76	18.41
T5	5.84	5.94	5.89	7.15	7.29	7.22	0.60	0.64	0.62	11.53	11.69	11.61	0.41	0.44	0.43	4.15	4.42	4.28	2.01	2.05	2.03	17.73	18.61	18.17
Means	5.82	5.90	**5.86 G.M[9]**	6.96	7.25	**7.10 G.M**	0.61	0.64	**0.627 G.M**	11.61	11.71	**11.66 G.M**	0.41	0.43	**0.42 G.M**	4.14	4.30	**4.22 G.M**	2.00	2.04	**2.02 G.M**	17.48	18.74	**18.11 G.M**
LSD	Fx: 0.18	Tx: 0.29	Fx*Tx :0.41	Fx: 0.47	Tx: 0.75	Fx*Tx :1.06	Fx: 0.04	Tx: 0.07	Fx*Tx : 0.10	Fx: 0.30	Tx: 0.48	Fx*Tx : 0.68	Fx: 0.03	Tx: 0.04	Fx*Tx :0.06	Fx: 0.28	Tx: 0.45	Fx*Tx :0.64	Fx: 0.08	Tx: 0.12	Fx*Tx : 0.17	Fx: 1.53	Tx: 2.42	Fx*Tx: 3.43
CV (%)		4.1			8.7			9.4			**3.4**			**9.1**			**8.8**			**5.1**			**11**	

MeanS without any letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

4 C: organic carbon

5 N: total nitrogen

6 P: available phosphorus (by Mehlich/ dilute double acid)

7 Fx: Methods of fertilizer application/ F1: row banding and F2: localised placement

8 Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time, T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

9 G.M: Grand mean

Table 4: Effect of timing and methods of N-P-K (17-17-17) fertilizer application on selected soil chemical properties at Kinigi site

Methods / Times	pH			C[10]			N[11]			P[12]			K^+			Ca^{2+}			Mg^{2+}			CEC		
	F1[13]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[14]	5.81	5.82	5.81	8.33	8.83	8.58	0.70	0.75	0.73	11.27	11.06	11.17	0.36	0.38	0.37	3.06	3.04	3.05	1.23	1.26	1.25	13.97	15.17	14.57
T2	5.80	5.87	5.84	9.00	9.17	9.08	0.76	0.84	0.80	11.09	11.90	11.49	0.41	0.44	0.42	3.15	3.42	3.29	1.52	1.75	1.64	15.30	16.87	16.08
T3	5.83	5.84	5.83	8.50	9.00	8.75	0.77	0.82	0.79	10.65	11.38	11.01	0.40	0.41	0.41	3.08	3.26	3.17	1.48	1.53	1.51	15.33	16.40	15.87
T4	5.80	5.87	5.84	9.00	9.17	9.08	0.78	0.82	0.80	11.19	11.80	11.49	0.38	0.46	0.42	3.20	3.40	3.30	1.49	1.61	1.55	15.73	16.50	16.12
T5	5.82	5.83	5.83	8.67	9.17	8.92	0.80	0.80	0.80	11.06	11.59	11.32	0.38	0.41	0.39	3.06	3.26	3.16	1.41	1.67	1.54	16.10	15.97	16.03
Means	5.81	5.84	5.83 G.M[15]	8.70	9.07	8.88 G.M	0.76	0.80	0.78 G.M	11.05	11.55	11.30 G.M	0.39	0.42	0.40 G.M	3.11	3.28	3.19 G.M	1.43	1.56	1.49 G.M	15.29	16.18	15.73 G.M
LSD	Fx: 0.06	Tx: 0.10	Fx*Tx :0.15	Fx: 0.54	Tx: 0.86	Fx*Tx : 1.21	Fx: 0.05	Tx: 0.09	Fx*Tx : 0.12	Fx: 0.70	Tx: 1.11	Fx*Tx :1.57	Fx: 0.05	Tx: 0.08	Fx*Tx :0.12	Fx: 0.18	Tx: 0.29	Fx*Tx :0.41	Fx: 0.22	Tx: 0.34	Fx*Tx :0.49	Fx: 1.13	Tx: 1.79	Fx*Tx :2.52
CV (%)		1.5			8			9.3			8.1			16.8			7.5			19.0			9.4	

Means without any letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

[10] C: organic carbon

[11] N: total nitrogen

12 P: available phosphorus (by Mehlich/ dilute double acid)

[13] Fx: Methods of fertilizer application/ F1: row banding and F2: localised placement

[14] Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time, T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[15] G.M: Grand mean

The increased N, P, K, Ca and Mg contents in the soil were products of increased organic carbon observed in the soil. This agreed with the report of Grichs (1990) that organic manure is a store house of plant nutrients and major contributor of cation exchange capacity and remained as buffering agent against pH fluctuation which plays a key role in sustaining desirable soil physical and chemical conditions for satisfactory growth and development of crops.

Organic matter shows a greater capacity to retain nutrients in form that can easily be taken up by a plant over long time. This results is consistent with the findings of Agbede *et al.* (2008), Kingery *et al*. (1993), Adeniyan and Ojeniyi (2005) that amendment of the soil using organic manure improves soil organic carbon, total nitrogen, available phosphorus and exchangeable Ca, Mg and K concentrations. The increase in soil-available P was not unexpected as the manure used was relatively rich in P. The increase in available P might also be owed to high microbial activity induced by the addition of organic residues, which might speed up phosphorus cycling (Parham *et al*., 2002). The nutrients in the N-P-K fertilizer (inorganic fertilizer) were already in the mineralized form and it provides a ready source of nutrients to the soils. Chemical fertilizer offers nutrients which are readily soluble in soil solution and thereby instantly available to plants. By implication, the nutrients released from N-P-K fertilizer were for a short period of time because they were either uptaken by crop or lost through leaching or other process like water runoff. Furthermore, several workers have reported longer residual effect of organic manures when applied to the soil (Adeniyan and Ojeniyi, 2003, Adetunji, 1997).

The organic fertilization allowed increases in the soil organic matter contents. That is due to the fact that the manure amendments on soil provide the nutritive elements by mineralization (Fan *et al.*, 2004; Wuest *et al.*, 2005). These results are almost similar to those of Wang *et al.* (2006) who observed that the cattle manure increased significantly the concentrations of the organic matter. The increase in the organic matter and organic carbon induced by the amendment is due to the manures which has three roles of organic matter sources, of protection of the soil against erosion and of increase in the number and activity of earthworms which reduce water runoff (Hole *et al*., 2005; Parfitt *et al*., 2005). The worms' casts have a strong assimilable nitrogen content, trace elements, organic matter, phosphorus and potassium (Flückiger *et al.*, 1998).

In accordance with the study's results and with those of Hao and Chang (2002), the cattle manure involved an increase in the sum of the exchangeable bases cations and the cation exchange capacity (CEC). Under the climatic conditions where the temperature and moisture are high or modelately high, the mineralization processes of the organic matter of the soil are intense (Thuriès *et al*., 2000). This trend is observed because of the usual greater microbial activities associated due to organic matter accumulation. These results are in agreement with the conclusions of other researchers (Thuriès *et al.*, 2000) who observed that the manure allowed significant increases in C, N and CEC soil contents. Indeed, the relatively fast mineralization of the organic matter provides the nutritive elements which constitute a surplus compared to the initial soil (Oehl *et al*., 2004). Similar results were obtained by Bado (2002), when he applied manure to soil of Farakô-Ba in Burkina-Faso.

The higher pH values observed after adding the organic manure and N-P-K indicates that organic manure has a tendency to neutralise soil acidity; the high Ca content of the organic manure was probably responsible for this effect. But, some authors such as Yaduvanshi (2003) have also reported a reduction in soil pH following the application of animal manure due to the production of CO_2 and organic acids during decomposition. Thus, the effect of organic manure on soil pH depends greatly on the latter's characteristics and condition. Then, the production of organic acids was not important with the organic manure used in this study. The study's results suggest that organic manures could increase pH of low pH soils by addition of base cations. This result is in agrrement with the findings of Whalen *et al.* (2000) who reported that cattle manure amended soil had significantly higher pH than non amended soil and the pH of Beaverlodge and Fort Vermillion soils increased from 4.8 to 6.0 and 5.5 to 6.3, respectively. In a system integrating farming and breeding, the use of the animal manure makes it possible to improve the soil properties, due to their very high organic matter contents. At the field, the manures improve the soil fertility. Such a system will allow a recycling of the nutritive elements ensuring a sustainable management of the soil fertility.

4.2 Effect of timing and methods of application of N.P.K fertilizer on emergence rate and number of shoots per plant

Tables 5 and 6 show the effect of timing and methods of N.P.K(17-17-17) fertilizer application on emergence rate and number of primary shoots (stems) per plant at Kibeho and Kinigi sites, respectively. At both sites, Kibeho and Kinigi, the crop behaviour was the same in terms of effects of times and methods of mineral fertilizer application on emergence rate and number of primary shoots per plant. Regarding emergence rate, it didn't differ significantly among times and methods of 17-17-17 fertilizer application. Times, methods of fertilizer application and even interaction of both factors had no significant influence on emergence rate (Appendix 1). However, the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE through localised placement method (F_2T_2) had the highest emergence rates, 100% and 95.33% at Kibeho and Kinigi, respectively.

At Kibeho site, the treatment that received a single application of the total mineral fertilizer rate at planting time and the one that received 75% of the fertilizer rate at planting time and the remaining at 28DAE had the highest (98.33%) and the lowest (96.33%) emergence rates, rspectively while localised placement (97.87%) performed better than row banding (96.40%). At Kinigi, the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE and other treatments except the one that received 75% of the fertilizer rate at planting time and the remaining at 28DAE, had the highest (95.00%) and lowest (94.00%) emergence rates, respectively while localised placement (94.67%) performed better than row banding (93.87%). The grand mean was 97.13% at Kibeho while it was 94.27% at Kinigi. The small difference between both sites resulted from cool temperatures prevailing at Kinigi which delay formation, growth and emergence of sprouts. The lack of significant effect of factors and their interaction resulted from the homogeneity of the variety used in terms of genetic make-up, seed tuber size, physiological age and sprout development level; the homogeneity within research field blocks and the very narrow variability range of abiotic factors of potato emergence, namely, soil temperature, soil moisture, soil type and planting depth. Another factor which caused the results similarity is the unique source of nutrients during the pre-emergence phase of the plants during this stage, the seed piece is the sole energy source for growth.

Table 5: Effect of timing and methods of N-P-K (17-17-17) fertilizer application on emergence rate (ER) and number of shoots per plant (N.S.P) at Kibeho site

Methods / Times	ER[16]28DAS[17]			N.S. P[18] 7DAE[19]			N.S. P 14DAE			N.S. P 21DAE			N.S. P 28DAE			N.S. P 35DAE		
	F1[20]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[21]	96.67	100	98.33	2.26	1.96	2.11	2.53	2.30	2.41	2.90	3.10	3.00	3.30	3.53	3.41	3.33	3.56	3.45
T2	96.67	98.67	97.67	2.30	1.90	2.10	2.53	2.30	2.41	2.90	2.93	2.91	3.36	3.23	3.30	3.36	3.20	3.28
T3	96.00	97.33	96.67	1.93	1.90	1.91	2.30	2.20	2.25	2.83	3.13	2.98	3.20	3.36	3.28	3.23	3.43	3.33
T4	96.00	97.33	96.67	2.30	1.93	2.11	2.46	2.23	2.35	2.90	3.13	3.01	3.26	3.26	3.26	3.23	3.36	3.30
T5	96.67	96.00	96.33	2.26	2.20	2.23	2.50	2.50	2.50	3.16	3.13	3.15	3.36	3.33	3.35	3.46	3.36	3.41
Means	96.40	97.87	97.13 G.M[22]	2.21	1.98	2.09 G.M	2.46	2.30	2.38 G.M	2.94	3.08	**3.01 G.M**	3.30	3.34	**3.32 G.M**	3.32	3.38	**3.35 G.M**
LSD	F_X: 2.44	T_x: 3.85	F_x*T_x: 5.45	F_X:0.25	T_x: 0.40	F_x*T_x: 0.56	F_X: 0.19	T_x: 0.30	F_x*T_x: 0.43	F_X: 0.19	T_x: 0.30	F_x*T_x: 0.42	F_X: 0.13	T_x: 0.22	F_x*T_x: 0.31	F_X: 0.25	T_x: 0.16	F_x*T_x: 0.36
CV (%)	3.3			15.8			10.5			8.2			5.5			6.4		

Means without any letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

[16] ER: Emergence rate (%)

[17] DAS: Days after sowing

[18] N.S.P: Number of stems(shoots) per plant

[19] DAE:Days after emergence

[20] Fx: Fertilizer application method: F1: Banding, F2: Localised Placement

[21] Tx: Timing of fertilizer application: T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively , T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[22] G.M: Grand mean

Table 6: Effect of timing and methods of N-P-K (17-17-17) fertilizer application on emergence rate and number of shoots per plant (N.S.P) at Kinigi site

	ER[23] 28DAS[24]			N.S. P[25] 7DAE[26]			N.S. P 14DAE			N.S. P 21DAE			N.S. P 28DAE			N.S. P 35DAE		
Methods Times	F1[27]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[28]	94.67	95.33	95.00	2.50	2.26	2.38	2.70	2.46	2.58	2.76	2.56	2.66	2.86	2.73	2.80	2.86	2.73	2.80
T2	93.33	94.67	94.00	2.40	2.40	2.40	2.60	2.70	2.65	2.83	2.83	2.70	2.86	2.90	2.88	2.80	2.90	2.85
T3	93.33	94.67	94.00	2.16	2.30	2.23	2.46	2.56	2.51	2.53	2.73	2.63	2.56	2.73	2.65	2.66	2.73	2.70
T4	94.00	94.00	94.00	2.30	2.20	2.25	2.70	2.63	2.66	2.83	2.63	2.73	2.96	2.63	2.80	2.93	2.63	2.78
T5	94.00	94.67	94.33	2.23	2.10	2.16	2.60	2.23	2.41	2.80	2.73	2.76	2.80	2.83	2.81	2.80	2.83	2.81
Means	93.87	94.67	**94.27**	2.32	2.25	2.28	2.61	2.52	**2.56**	2.75	2.70	**2.72**	2.81	2.76	**2.79**	2.81	2.76	**2.79**
			G.M[29]						**G.M**			**G.M**			**G.M**			**G.M**
LSD	F_x: 1.47	T_x: 2.33	F_x*T_x: 3.29	F_X: 0.18	T_x: 0.28	F_x*T_x: 0.40	F_X: 0.20	T_x: 0.32	F_x*T_x: 0.45	F_X: 0.16	T_x: 0.25	F_x*T_x: 0.36	F_X: 0.17	T_x: 0.28	F_x*T_x: 0.39	F_X: 0.16	T_x: 0.26	F_x*T_x: 0.36
CV (%)		2.0			10.2			10.3			12.2			8.2			7.6	

Means without any letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

[23] ER: emergence rate (%)

[24] DAS: Days after sowing

[25] N.S.P: Number of stems(shoots) per plant

[26] DAE:Days after emergence

[27] Fx: Fertilizer application method: F1: Banding, F2: Localised Placement

[28] Tx: Timing of fertilizer application: T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively , T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[29] G.M: Grand mean

The results are consistent with the findings of Lang *et al.* (1999) according to which the rate of potato shoot emergence depends on soil temperature; under favorable growing temperatures (typically 55 to 65°F/ 12.7 to 18.3^{o}c during early spring), shoots emerge within 21 days after sowing (DAS). The research results are in agreement with the findings of research undertaken under the Ministry of Agriculture, Food and Rural Affairs (2011) which showed soil moisture and soil temperature as main abiotic factors influencing the length of time between planting and emergence. The findings of the present study agree with the ones of University of California, Division of Agriculture and Natural Resources (1986) which found that the rate of sprout growth and, consequently, the time until emergence are temperature dependent and therefore somewhat dependent on soil type and planting depth. The author declared that the seed tuber is the only source of energy for the plants' growth. Moreover, the author indicated that there is usually enough starch in sound and properly sized potato seed piece to support sprout growth for 30 days or longer.

The results of this study also confirm the findings of Pavek *et al.* (2006) who found that soil moisture and temperature are most commonly the major factors that contribute to potato sprout growth and emergence rate. Additional factors include seed size and health, sprout health, sprout/eye location on the mother seed tuber, soil fertility, cultivar, mother-tuber physiological age, volume and mechanical resistance of soil, and seed tuber dormancy. The results also confirm the findings of Milthorpe (1967) who showed that the mother tuber provides the main source of substrate until the plants have a leaf surface of 200-400 cm^2. Headford (1961) and White (1961) reported the same observation. The difference raised between both study sites is also consistent with study conducted by Milthorpe (1967) who demonstrated that if there is an adequate supply of water, growth during the pre-emergence phase is controlled by soil temperature and by the degree of sprout development at planting. Generally, the rate of emergence of potato seedlings is faster the higher the soil temperature and the greater the degree of development of the sprouts at planting. The meteorological data collected during the field experiment showed that Kinigi site was always characterized by low temperatures which was probably the reason for the low emergence rate of the plants there. Curiously, the results don’t agree with the findings of Mahmood *et al.* (2002) who found that emergence rate of potato was significantly influenced by methods of fertilizer application.

Concerning the number of primary shoots (stems or haulms) per plant, the methods of mineral fertilizer application, the timing of its application and their interaction were all not significant at both sites and during the whole period of the experiment, but their number increased with the time (Appendices 2-6). However, the highest number of shoots per plant (3.56 and 2.90 at Kibeho and Kinigi, respectively) were recorded from the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE through row banding method (F_2T_1) and the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE through localised placement method (F_2T_2). At Kibeho, the treatment that received a single application of the mineral fertilizer total rate and the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE had the highest (3.45) and lowest (3.28) number of shoots per plant, respectively while localised placement (3.38) performed better than banding (3.32). At Kinigi, the treatment that received 50% of the mineral fertilizer rate at planting and the remaining at 14DAE and the treatment that received 75% of the mineral fertilizer rate at planting and the remaining at 14DAE had the highest (2.85) and lowest (2.70) number of stems per plant, respectively while row banding (2.81) performed better than placement (2.76).

The grand means were 3.35 and 2.79 at Kibeho and Kinigi, respectively. The lack of significant difference is attributed to the fact that the number of shoots per plant depends mainly on genetic potential (genetic make-up) of the variety, development phases of sprouts at planting time, grade (size) and the number of eyes of mother-tuber. Environmental major factors that influence the number of shoots are temperature and soil nutrients (nitrogen particularly). Since the fertilizer rate applied in the field experiment was the same, it was not considered as a variable even if it was split into two portions for some treatments, the total quantity was always the same and applied all the time during the period of primary shoots sprouting and development. High temperatures prevailing at Kibeho during the crop cycle stimulated development of more sprouts, this most likely led to a bit higher mean of the number of shoots per plant. The results found are consistent with the findings of Roy *et al.* (2006) which recognized the role of N in branching-tillering phenomenon.In the present experiment, the same rate of fertilizer (containing the same quantity of nitrogen) was applied; hence there was no reason to find significant differences among treatments. The results are in agreement with research findings of Susnochi (1982) and

Morena *et al.* (1994) according to which the active number of Irish potato haulms per plant is a variable that is mostly affected by cultivar characteristics even if diseases and environmental stresses play an important role too. Both last factors were not considered as variables during the present research as the only cruza variety was used and diseases were controlled in the same conditions.

The results are also in harmony with the findings of Morena *et al.* (1994) and Gill *et al.* (1989) show that the number of active Irish potato haulms may vary a lot depending on seed age, mass, size and the number of growing eyes or sprouts; but the number of eyes and distribution are characteristic of the variety. The seed uniformity in terms of those parameters was checked before planting. The role of N availability as a factor influencing tillering has also been discussed by Assuero and Tognetti (2010). These authors suggested that N plays a strong mediatory role in tiller production through cytokinin production by roots, since production of this hormone is mediated by N concentration in the roots which, in turn, is a function of N absorption from the soil and seasonal reallocation of tissue N. Since the same and total mineral fertilizer rate was applied in the present experiment during probably haulms development period, nitrogen rate could not significantly influence treatment in terms of haulms number per plant.

The differences observed between results from both sites are consistent with the findings of a research conducted by Assuero and Tognetti (2010) which indicated that low temperatures reduce tillering (number of tillers per plant). Therefore, the low number of haulms per plant found at Kinigi should be due to the low temperatures prevailing there during the crop growth cycle.

4.3 Effect of timing and methods of N-P-K application on Irish potato stem height (cm) and canopy cover (%)

4.3.1 Effect of timing and methods of N-P-K application on stem height

- **Period of 1st 28 days after emergence**

At both sites, Kibeho and Kinigi, methods of mineral fertilizer application were highly significant ($P<0.001$) while timing of application and interaction between methods and timing were not significant ($P>0.05$); but stem height increased with the time (Appendices 7-8). At 28 days after emergence however, the highest height (32.23cm and 25.70cm at Kibeho and Kinigi, respectively) were observed in the treatments which received split application; 50% and 75% of the total fertilizer rate at planting and the remaining at 14DAE, through localised placement fertilizer application method (F_2T_2 and F_2T_3) at kibeho and the treatment which received 100% of the total fertilizer rate at planting time through localised placement fertilizer applicaqtion method (F_2T_1) at Kinigi. At Kibeho site, the treatment which received 100% of the total fertilizer rate at planting time and the treatment that received 75% of the total fertilizer rate at planting and the remaining at 14DAE had the highest (32.33cm) and lowest (29.93cm) stem height, respectively while localised placement (32.79cm) performed better than banding (28.60cm).

At Kinigi site, the treatment which received 100% of the total fertilizer rate at planting time and the treatment that received 50% of the total fertilizer rate at planting and the rest at 28DAE had the highest (25.70cm) and lowest (24.53cm) stem height, respectively while localised placement (26.85cm) performed better than row banding (22.71cm). The grand mean was 30.70cm at Kibeho site while it was 24.78cm at Kinigi site. At both sites, localised placement method led to taller crops compared to row banding. The significant difference between localised placement and row banding could be due to the weak and short root system of Irish potato which was not yet even fully developed to maximize nutrient absorption rate and root zone exploitation.

Table 7: Effect of timing and methods of N-P-K (17-17-17) fertilizer application on Irish potato stem height (cm) and canopy cover (%) at Kinigi

	Stem Height 14DAE [30]			Stem Height 28DAE			Stem Height 42DAE			Stem Height 56DAE			Stem Height 70DAE			Canopy cover (%)		
Methods Times	F1[31]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[32]	12.87	14.83	13.85	24.33	27.07	25.70	43.90	45.70	44.80 **b**	54.63	61.50	58.07 **b**	59.53	61.43	60.48 **b**	62.8	78.3	70.6**c**
T2	11.53	13.40	12.47	21.87	27.23	24.55	52.00	61.90	56.95 **a**	64.40	70.90	67.65 **a**	67.87	75.00	71.43 **a**	83.3	106.7	95.0**a**
T3	12.13	14.60	13.37	21.87	27.27	24.57	50.13	53.87	52.00 **a**	62.30	67.20	64.75 **a**	67.70	71.23	69.47 **a**	79.5	92.2	85.8**ab**
T4	11.53	13.43	12.48	22.67	26.40	24.53	51.87	53.63	52.75 **a**	63.53	71.27	67.40 **a**	67.73	72.33	70.03 **a**	80.7	89.7	85.2**ab**
T5	12.33	14.40	13.37	22.80	26.27	24.53	51.10	55.57	53.33 **a**	63.13	66.80	64.97 **a**	67.70	72.33	70.02 **a**	71.5	87.5	79.5**bc**
Means	12.08 **b**	14.13 **a**	13.10 G.M[33]	22.71 **b**	26.85 **a**	24.78 G.M	49.80 **b**	54.13 **a**	51.97 G.M	61.60 **b**	67.53 **a**	64.57 G.M	66.11 **b**	70.47 **a**	68.29 G.M	75.6**b**	90.9**a**	83.2 G.M
LSD	F_X:	T_x:	F_x*T_x:	F_X:	T_x:	F_x*T_x:	F_X:	T_x:	F_x*T_x:	F_X:	T_x:	F_x*T_x:9	F_X:	T_x:	F_x*T_x:	F_X:	T_x:	F_x*T_x:
	0.90	1.43	2.02	1.43	2.27	3.21	3.06	4.85	6.86	4.15	6.56	.27	3.91	6.19	8.75	6.20	9.80	13.85
CV (%)		9.0			7.6			7.7			8.4			7.5			9.7	

Means without any letter or with the same letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

[30]DAE: Days after emergence

[31] Fx: Fertilizer application method: F1: Banding, F2: Localised Placement

[32] Tx: Timing of fertilizer application: T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively , T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[33] G.M: Grand mean

Table 8: Effect of timing and methods of N-P-K application on Irish potato stem height (cm) and canopy cover (%) at Kibeho

	Stem Height 14DAE[34]			Stem Height 28DAE			Stem Height 42DAE			Stem Height 56DAE			Stem Height 70DAE			Canopy cover (%)		
Methods Times	F1[35]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[36]	14.83	16.83	15.83	31.90	32.77	32.33	48.83	50.67	49.75**b**	58.23	65.10	61.67**b**	61.23	68.10	64.67**b**	65.6	74.7	70.2**c**
T2	13.53	15.33	14.43	28.67	33.23	30.95	57.03	66.87	61.95**a**	68.03	74.50	71.27 **a**	71.03	77.50	74.27**a**	79.0	99.2	89.1**a**
T3	14.17	16.60	15.38	26.63	33.23	29.93	55.13	59.30	57.22**a**	68.03	70.80	68.35**a**	68.90	73.80	71.35**abc**	76.2	83.3	79.8**b**
T4	13.53	15.47	14.50	27.90	32.40	30.15	56.90	58.53	57.72 **a**	67.27	74.87	71.07 **a**	70.93	77.87	74.40**a**	74.8	84.5	79.7**b**
T5	14.27	16.40	15.33	27.90	32.3	30.12	56.03	60.53	58.28**a**	66.73	70.53	68.63 **a**	69.70	73.47	71.58**ab**	71.0	82.7	76.8**bc**
Means	14.07 **b**	16.13 **a**	15.10 G.M[37]	28.60 **b**	32.79 **a**	30.70 G.M	54.79**b**	59.18**a**	56.98 G.M	65.23**b**	71.16**a**	68.20 G.M	68.36 **b**	74.15 **a**	71.25 G.M	73.3**b**	84.9**a**	79.1 G.M
LSD	F_X:0.90	T_x:1.44	F_x*T_x: 2.03	F_X: 1.42	T_x: 2.24	F_x*T_x: 3.17	F_X: 3.05	T_x: 4.83	F_x*T_x: 6.84	F_X: 4.16	T_x: 6.57	F_x*T_x: 9.29	F_X: 4.18	T_x: 6.61	F_x*T_x: 9.35	F_X: 5.36	T_x:8.48	F_x*T_x: 11.99
CV (%)		7.8			6.0			7.0			7.9			7.7			8.8	

Means without any letter or with the same letter along the row for the fertilizer application methods (Fx) and along the column for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

[34] DAE: Days after emergence

[35] Fx: Fertilizer application method: F1: Banding, F2: Localised placement

[36] Tx: Timing of fertilizer application: T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively , T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[37] G.M: Grand mean

Timing didn't show a significant effect because the next split fertilizer portions were added to the soil before the single application and previous portions had been completely removed from the root zone. The recommended fertilizer rate applied at planting (T_1) was still present in the root zone and was sufficient to cover equally the crop requirements. The differences between sites in terms of means and grand means are attributed to cool temperatures and high differences between day and night temperatures prevailing at Kinigi site. Both factors are known to delay crop development, thereby lengthening growth and bulking period (Western Potato Council. 2003).

- **Period 42-70 days after emergence**

At both sites, timing was highly significant ($P<0.01$ at 42 days after emergence) and significant ($P<0.05$ at 56 and 70 days after emergence) while methods were highly significant ($P<0.01$ at 42 and 56 days after emergence at Kibeho and Kinigi, 70 days after emergence at Kibeho) and significant ($P<0.05$ at 70 days after emergence at Kinigi). The interaction between methods and timing of fertilizer application was all the time not significant ($P>0.05$); but stem height increased with the time (Appendices 9-11). At both sites, localised placement method gave taller crops compared to banding method. At 70 days after emergence, highest stem height (77.87cm and 75.00cm at Kibeho and Kinigi, respectively) were recorded in the treatment which received, by localised placement fertilizer application method, 50% of the total fertilizer rate at planting and the remaining at 28DAE at Kibeho and the treatment which received, by localised placement application method, 50% of the total fertilizer rate at planting time and the remaining at 14DAE at Kinigi.

Duncan Multiple Range Test classified times of fertilizer application in two distinct groups (a and b), the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE came all the time in 1st position (74.27cm and 71.43cm at Kibeho and Kinigi, respectively) while the treatment which received 100% of the total fertilizer rate at planting time occupied all the time the last place (64.67cm and 60.48cm at Kibeho and Kinigi, respectively). The methods of fertilizer application formed two groups, the 1st was made by localised placement (74.15cm and 70.47cm at Kibeho and Kinigi sites, respectively) while the

2^{nd} and the last was made by row bamding (68.36cm and 66.11cm at Kibeho and Kinigi sites, respectively) .

The best result of localised placement is attributed to the fact that little or no fertilizer is wasted as all nutrients come in close contact with feeding roots, which are weak and less developed, and plant use those nutrients efficiently. Some wastage of fertilizer may take place in banding while some may be localized too far away from the root system. Split application fertilizer gave taller crops compared to single application. Split application reduces fertilizer leaching losses by matching fertilizer applications with crop nutrient uptake and synchronizes nutrient availability with crop demand. All other treatments are significantly different from the treatment which received 100% of the total fertilizer rate at planting time (T_1) while all of them are not significantly different from each other.

At both sites, the treatment which received 50% of the total fertilizer rate at planting time and the remaining at weeding was the tallest while the treatment which received 100% of the total fertilizer rate at planting time was the shortest. The results seem to show that much of leached fertilizer came from the portion applied at planting time because at this stage the crop root system was not yet well fully developed to maximize nutrient absorption. The application of 50% of the total fertilizer rate at planting time and the remaining at 14DAE was the optimal way to match fertilizer application with crop nutrient uptake and to synchronize nutrient availability with potato demand within time and over all crop growth and development phases. Moreover, the timing effect became significant during this second period because the root system had developed sufficiently to reach the maximum of its potential root zone and optimize nutrient absorption.

The differences between sites in terms of means and grand means of stem height resulted from cool temperatures and high differences between day and night temperatures at Kinigi. Both factors delay crop growth and development, thereby lengthen Irish potato growth and bulking period. The results are in agreement with the findings of Jones and Jacobsen (2009) who emphasized the positive effect, on fertilizer use efficiency in general and Irish potato crop growth and yield in particular, of split application and closer placement (on the seed, seedling or crop) of N and K fertilizers. The research results are in harmony with the research outcomes of Cumings *et al.(*1939) who showed the superiority of closer fertilizer placement to other methods of N, P and K fertilizers application for potatoes. The results also confim the findings of Hochmuth *et al.* (2000) concerning N-P- K fertilizer use for Irish potato production. The research found a positive effect of closer placement of N-P-K fertilizers and split application on Irish potato performance in Florida. The results also agree with the findings of so many other workers like Lang *et al. (*1999), Alberta (2002), Cauley *et al.* (2004), Roy *et al.* (2006), Jones and Jacobsen (2009).

4.3.2 Effect of timing and methods of N-P-K application on canopy cover

At both sites, Kibeho and Kinigi, effects of timing and methods of mineral fertilizer application on canopy cover were highly significant ($P<0.001$) while effects of interaction between methods and timing of fertilizer application were not significant ($P>0.05$) (Appendix 12). However, the largest canopy cover (99.2% and 106.7% at Kibeho and Kinigi, respectively) was found from the treatment which received, through localised placement fertilizer application method, 50% of the total fertilizer rate at planting and the remaining at 14DAE while the narrowest canopy cover (62.8% and 65.6% at Kinigi and Kibeho, respectively) was measured in the treatment which received, by row banding fertilizer application method, 100% of the total fertilizer rate at planting time.

At both sites, the treatment which received 50% of the total fertilizer rate at planting and the remaining at 14DAE (89.1% and 95.0% at Kibeho and Kinigi, respectively) had the largest canopy cover and the treatment which received 100% of the total fertilizer rate at planting time (70.2% and 70.6% at Kibeho site and Kinigi site, respectively) had the narrowest canopy cover while localised placement (84.9% and 90.9% at Kibeho and Kinigi, respectively) performed better than row banding (73.3% and 75.6% at Kibeho and Kinigi, respectively). The grand mean was 79.1% at Kibeho site while it was 83.2% at Kinigi site. At both sites, localised placement method resulted in larger canopy covers compared to row banding which resulted in narrow canopy covers. The significant difference between localised placement and banding could be due to the fact that little or no fertilizer is wasted in localized placement method as all nutrients come in close contact with feeding roots, which are weak and less developed, and plants use those nutrients efficiently to develop more vegetative biomass (Mahmood *et al.* (2002). Some wastage of fertilizer may occur in row banding while some may not be reached by the crop root system (Mahmood *et al.,2*002). Split application of fertilizer resulted in a large canopy cover compared to single application (Gathungu *et al*., 2000).

The best result of split application is attributed to the fact that it reduces fertilizer leaching losses by matching fertilizer applications with crop nutrient uptake and by synchronizing nutrient availability and crop demand (Gathungu *et al*., 2000). All other treatments are significantly different from the treatment which received 100% of the total fertilizer rate at planting time while all of them are not significantly different from each other except the treatment which received 50% of the total fertilizer rate at planting and the remaining at 14DAE which was the 1st. The application of 50% of the total fertilizer rate at planting time and the remaining at 14DAE was the optimal way to match fertilizer application with crop nutrient uptake and to synchronize nutrient availability and potato demand within time and over all crop growth and development phases. Split application and localized placement resulted in taller plants which should normally have a large number of branches and leaves. Both branches and leaves are components of the crop canopy. These growth characteristics should result from a vigorous root system which is well developed and properly established. Taller plants with a vigorous root system, and a large number of branches and leaves are expected to produce a large canopy cover.

The timing of application of fertilizer (especially N) is an important factor which determines the rate of vegetative growth (leaves and branching) and canopy cover standing and structure. The key to plant growth and development depends on the establishment of vigorous and well developed root system, a strong and well shaped branching type and a healthy large LAI that is durable through the reproductive phase, achieved through adequate N, P, K and water supply in addition to solar radiation (Gathungu *et al*., 2000). Taller plants, normally with normally high number of leaves, large canopy cover and probably greater LAI (Leaf Area Index), were observed in potatoes that received split application of fertilizer through localized placement method. Hence, split application combined with localized placement of the fertilizer enabled a high interception of solar radiation, mainly due to the taller plants with normally high number of leaves and branches, large canopy cover and greater photosynthetic surface area of the crop

(LAI). This resulted in increased photosynthetic capacity and supply of the photoassimilates leading to increased growth (Gathungu *et al*., 2000). Single application resulted in shorter plants with normally low number of leaves, low number of branches leading to a narrow canopy cover, low LAI and less developed root system during the important period of growth stages.

The results agree with the findings of Hopkins *et al.* (2008), who demonstrated that potatoes require a modest amount of N early in the season for adequate canopy development. The same authors also found that mid-season deficiencies of N reduce canopy growth and often cause premature senescence, which can reduce yields. Besides, they argued that excess mid-season N slows tuber bulking in favor of vegetative growth. This study's results are also consistent with the research findings of other researchers who found that synchronizing N availability and potato demand is recommended in order to maximize potato growth and development, tuber yield, tuber quality, and N efficiency (Errebhi *et al*. (1998), Gayler *et al.* (2002), Munoz *et al.* (2005), Stark *et al.* (2003), Waddell *et al.* (2000) and Westermann (2005)). The results confirm the findings of Roy *et al.* (2006), Jones Jacobsen. (2009) and Alberta (2002) who recommended placement of P and K fertilizers close to the root system and split application of these fertilizers in order to minimize fixation of P and leaching of K. Moreover, Mahmood *et al.* (2002) focused a research on comparing different methods of fertilizer application vs broadcasting, placement and banding in Islamabad (Pakistan), they found that in terms of canopy cover, banding and placement were in the same homogenous group but placement gave larger canopy cover on average than banding.

4.4 Effect of timing and methods of N-P-K application on Irish potato yield components and total tuber yield

4.4.1 Effect of timing and methods of N-P-K application on the number of potato tubers per plant

At both sites Kibeho and Kinigi, methods and timing of fertilizer application were highly significant ($P<0.001$) while interaction between methods and timing of fertilizer application was not significant ($P>0.05$) (Appendix 13). However, more tubers per plant (12.03 and 16.07 at Kibeho site and Kinigi site, respectively) were obtained from the treatments which received split application, using localised placement method, with 50% of the total fertilizer rate at planting time and the remaining at 14DAE (F_2T_2); fewer tubers per plant (8.57 and 8.13 at Kibeho site and Kinigi site, respectively) were obtained from the treatments which received single fertilizer application using row banding method (F_1T_1).

Table 9: Effect of timing and methods of N-P-K application on potato yield components and tuber yield at Kibeho site

	Number of tubers per plant			Total tuber yield (t ha^{-1})			Medium size yield (t ha^{-1})			Small size yield (t ha^{-1})		
Methods / Times	F1[38]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[39]	8.57	9.63	9.10 **c**	8.70	11.83	10.27**c**	7.53	9.90	8.72 **c**	2.03	3.50	2.767**b**
T2	10.00	12.03	11.02**a**	12.70	16.77	14.73 **a**	10.53	13.60	12.07 **a**	3.20	4.86	4.03 **a**
T3	9.80	11.17	10.48**ab**	11.70	13.20	12.45 **b**	9.80	10.90	10.35 **b**	3.46	3.83	3.65 **a**
T4	9.73	11.17	10.45**ab**	12.23	13.80	13.02 **b**	10.20	11.33	10.77 **b**	3.60	4.00	3.80 **a**
T5	9.70	10.13	9.92 **bc**	10.67	13.43	12.05 **b**	9.00	11.07	10.03 **b**	3.13	3.93	3.53 **a**
Means	9.56**b**	10.83**a**	**10.19 G.M[40]**	11.20**b**	13.81 **a**	**12.50 G.M**	9.41 **b**	11.36 **a**	**10.39 G.M**	3.08 **b**	4.02 **a**	**3.55 G.M**
LSD	F_X: 0.62	T_x: 0.98	F_x*T_x: 1.39	F_X: 1.07	T_x: 1.69	F_x*T_x: 2.39	F_X: 0.81	T_x: 1.28	F_x*T_x: 1.81	F_X: 0.38	T_x: 0.60	F_x*T_X: 0.85
CV (%)	8.0			11.1			10.2			14.0		

Mean without any letter or with the same letter along the row for the fertilizer application methods (Fx) and along the colum for the times of the fertilizer application (Tx) are not significantly different at LSD ≤ 0.05.

[38] Fx: Methods of fertilizer application/ F1: banding, F2: localised placement

[39] Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[40] G.M: Grand mean

Table 10: Effect of timing and methods of N-P-K application on potato yield components and tuber yield at Kinigi site

	Number of tubers per plant			Total tuber yield (t ha^{-1})			Big size yield (t ha^{-1})			Medium size yield (t ha^{-1})			Small size yield (t ha^{-1})		
Methods Times	F1[41]	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means	F1	F2	Means
T1[42]	8.13	9.53	8.83 **b**	9.97	13.67	11.82**c**	2.433	3.40	2.91**c**	5.00	6.77	5.88**c**	2.53	3.50	3.01 **c**
T2	11.50	16.07	13.78**a**	14.67	19.33	17.00**a**	3.667	4.80	4.23 **a**	7.30	9.67	8.48**a**	3.70	4.86	4.28 **a**
T3	10.80	14.00	12.40**a**	13.50	16.03	14.77**b**	3.333	4.06	3.70 **b**	6.70	9.67	7.37**b**	3.46	3.93	3.70 **b**
T4	11.93	14.00	12.97**a**	14.13	15.93	15.03 **b**	3.500	3.96	3.73**ab**	7.03	8.00	7.52**ab**	3.60	4.00	3.80 **b**
T5	11.00	12.63	11.82**a**	12.30	15.50	13.90 **b**	3.000	3.73	3.36**bc**	6.17	7.83	7.00**b**	3.13	3.93	3.53 **b**
Means	10.67 **b**	13.25**a**	11.96 G.M[43]	12.91**b**	16.09 **a**	14.50 G.M	3.187 **b**	3.99 **a**	3.59 G.M	6.44**b**	8.06**a**	7.25 G.M	3.28 **b**	4.04 **a**	3.66 G.M
LSD	F_X: 1.16	T_x: 1.83	F_x*T_x: 2.58	F_X: 1.24	T_x: 1.96	F_x*T_x: 2.77	F_X: 0.32	T_x:0.50	F_x*T_x: 0.71	F_X: 0.63	T_x: 1.00	F_x*T_x: 1.41	F_X: 0.30	T_x: 0.48	F_x*T_x: 0.68
CV (%)		12.6			11.1			11.6			11.4			10.9	

Mean without any letter or with the same letter along the row for the fertilizer application methods (Fx) and along the colum for the times of the fertilizer application (Tx) are not significantly different at LSD $\leq$ 0.05.

41 Fx: Methods of fertilizer application/ F1: banding and F2:localised placement

42 Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

43 G.M: Grand mean

At the two sites, the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE was the 1st (11.02 and 13.78 at Kibeho and Kinigi sites, respectively) while the treatment which received single fertilizer application occupied the last place (9.10 and 8.83 at Kibeho and Kinigi sites, respectively). Localised placement (10.83 and 13.25 at Kibeho and Kinigi, respectively) performed better than row banding in both locations (9.56 and 10.67 at Kibeho site and Kinigi site, respectively. Duncan's Multiple Range Test classified times of application in different groups: a (T_2), ab (T_3 and T_4), bc (T_5) and c (T_1) at Kibeho; and a (T_2[44]) and b (T_1, T_3, T_4 and T_5) at Kinigi. The grand mean was 10.19 at Kibeho while it was 11.96 at Kinigi. At both sites, localised placement method produced more tubers per plant compared to row banding. The best results of localised placement (F_2[45]) are due to the fact that little or no fertilizer was wasted as all the nutrients come in close contact with feeding roots and the plants use those nutrients efficiently. Some wastage of fertilizer may occur in banding due to leaching or to the roots being unable to reach the fertilizer localized too far from them. Split-application of fertilizer yielded more tubers per plant compared to single application.

The best result of split application is due to the fact that it reduces nutrient leaching losses by matching fertilizer applications with crop nutrient uptake and by synchronizing nutrient availability and potato demand. The treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE yielded more tubers per plant than the others. This performance of this treatment in terms of the number of tubers per plant could be due to the fact that it received the best averaged portion of fertilizer (50%) at planting time and the remaining at 14DAE, the period of tuberization initiation, while others (T_1, T_3 andT_5) received at least 75% of the recommended rate at planting time, the period during which the rate of leaching was the highest and the crop root system was not yet well developed. Compared to the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 28DAE (T_4), the

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[44] Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

[45] Fx: Methods of fertilizer application/ F1: banding and F2: localised placement

difference is attributed to the fact that T_4 received the second half a bit late (at earthing up time), tuberization had already started. The supplementary fertilizer portion should be more channeled for shoot growth and development than for tuber formation and bulking or swelling. A split application with 50% of the total fertilizer rate applied at planting time and the remaining at 14DAE (T_2) was the optimal way to match fertilizer applications with crop nutrient uptake and to synchronize nutrient availability and potato demand within time and over all crop growth and development phases.

The differences between Kibeho and Kinigi sites in terms of means, grand means and the number of groups (referring to Duncan's Multiple Range Test), are attributed to cool temperatures and high differences between day and night temperatures at Kinigi. Both factors are known to delay crop development, thereby lengthening growth and bulking period. At Kinigi treatments got more time to recover small differences raising intermediate groups at Kibeho.

4.4.2 Effect of timing and methods of N-P-K application on total tuber yield

At both sites, Kibeho and Kinigi, effects of methods and timing of fertilizer application were highly significant ($P<0.001$) while effects of interaction between both factors were not significant ($P>0.05$)(Appendix 14). However, higher yields (16.77 t/ha and 19.33 t/ha at Kibeho site and Kinigi site, respectively) were obtained from the treatments which received split application, by localised placement fertilizer application method, with 50% of the total fertilizer rate at planting and the remaining at 14DAE (F_2T_2); lower yields (10.27 t/ha and 11.82 t/ha at Kibeho site and Kinigi site, respectively) were measured in the treatments which received single application of the fertilizer by row banding method (F_1T_1). At the two sites, the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE (T_2) came in 1^{st} position (14.73 t/ha and 17.00 t/ha at Kibeho site and Kinigi site, respectively) while the treatments which received single application of the fertilizer at planting time (T_1) occupied the last place (10.27 t/ha and 11.82 t/ha at Kibeho site and Kinigi site, respectively). Locaalised placement (13.81 t/ha and 16.09 t/ha at Kibeho site and Kinigi site, respectively) performed better, in both locations, than row banding (11.23 t/ha and 12.9 1t/ha at Kibeho site and Kinigi site, respectively). Duncan's Multiple Range Test classified times of application, over both sites, in different groups: a (T_2[46]), b (T_3, T_4 and T_5) and c (T_1). The grand mean was 12.50 t/ha at Kibeho site while it was 14.56 t/ha at Kinigi site. The overall increase in yield with localised placement method over row banding was 23.30% and 24.63%, respectively at Kibeho site and Kinigi site. The increase with T_2, T_4, T_3 and T_5 over T_1 was 43.43%, 26.78%, 21.23%, 17.33% and 43.82%, 27.16%, 24.96%, 17.60% at Kibeho site and Kinigi site, respectively. At both sites, localised placement method produced more tubers per plant than banding.

The best result of localised placement is due to the fact that little or no fertilizer was wasted as all the nutrients come in close contact with feeding roots and plants use those nutrients efficiently. Some wastage of fertilizer may occur in banding while some may be localized too far away from the root zone to be reached and absorbed. Split application of the fertilizer yielded more total tuber yields than single application. Split application reduces fertilizer leaching losses by matching fertilizer applications with crop nutrient uptake and synchronizes nutrient availability with crop demand. The treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE (T_2) yielded more total tuber yield than the others. This performance of the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE in terms of the total tuber yields could be due to the fact that it received the best averaged portion of fertilizer: (50%) at planting time and the remaining at 14DAE, the period of tuberization initiation, while the others (T_1, T_3 and T_5) received at least 75% of the recommended rate at planting time, the period during which the rate of leaching was the highest and the crop root system was not yet well developed. Compared to the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 28DAE (T_4), the difference is attributed to the fact that T_4 received the second half four weeks after emergence (a bit late and at earthing up time), tuberization had already started. The supplementary fertilizer portion should be more channeled for shoot growth and development than for tuber formation and bulking (swelling). A split application with 50% of the total fertilizer rate applied at

[46]Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

planting time and the remaining at 14DAE (T_2) was the optimal way to match fertilizer applications with crop nutrient uptake and to synchronize nutrient availability and potato demand within time and over all crop growth and development phases.

The differences between Kibeho and Kinigi sites in terms of means, grand means and the number of groups (referring to Duncan's Multiple Range Test), are attributed to cool temperatures and high differences between day and night temperatures at Kinigi. Both factors are known to delay crop development, thereby lengthening growth and bulking period. At Kinigi treatments got more time to recover small differences raising intermediate groups at Kibeho.

4.4.3 Effect of timing and methods of N-P-K application on tuber grades yield

Large size tubers*:* only Kinigi site produced tubers of large size, Kibeho site didn't produce any. Timing and methods of fertilizer application were highly significant ($P<0.001$) while the interaction between methods and timing of fertilizer application was not significant ($P>0.05$)(Appendix 15). However, the highest large size tuber yield (4.8 t/ha) was obtained from the treatments which received split application of the fertilizer applied by localised placement, with 50% of the total fertilizer rate applied at planting time and the remaining at 14DAE (F_2T_2) while the lowest large size tuber yield (3.4 t/ha) was obtained from the treatments which received, by banding method, a single application of the total fertilizer rate (F_1T_1). The treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14AED (T_2) was the 1st (4.2 t/ha) while the treatments which received single application of the total fertilizer rate at planting time (T_1) occupied the last place (2.9 t/ha). Localised placement (3.99 t/ha) performed better than row banding (3.18t/ha). Duncan's Multiple Range Test classified times of application in different groups: a (T_2[47]), b (T_3), ab (T_4), bc(T_5) and c (T_1). The grand mean was 3.59 t/ha.

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[47] Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

Medium size tubers: at both sites, Kibeho and Kinigi, effects of methods and timing of fertilizer application were highly significant ($P<0.001$) while effects of interaction between both factors were not significant ($P>0.05$)(Appendix 15). However, the highest medium size tuber yields (13.60 t/ha and 9.67 t/ha at Kibeho and Kinigi, respectively) were obtained from the treatments which received split application, by localised placement fertilizer application method, with 50% of the total fertilizer rate applied at planting and the remaining at 14DAE (F_2T_2) and the lowest medium size tuber yields (7.53 t/ha and 5.00 t/ha at Kibeho and Kinigi sites, respectively) were obtained from the treatments which received single application of the fertilizer by banding method (F_1T_1). At the two sites, the treatment which received 50% of the total fertilizer rate at planting time and the remaining at 14DAE (T_2) occupied the 1st place (12.07 t/ha and 8.48 t/ha at Kibeho and Kinigi sites, respectively) while the treatments which received single application of the total fertilizer rate at planting time (T_1) occupied the last place (8.72 t/ha and 5.88 t/ha at Kibeho and Kinigi sites, respectively). Localise placement (11.36 t/ha and 8.06 t/ha at Kibeho site and Kinigi site, respectively) performed better, in both locations, than row banding (9.41 t/ha and 6.44 t/ha at Kibeho site and Kinigi site, respectively). Duncan's Multiple Range Test classified times of application, in different groups: a (T_2[48]), b (T_3, T_4 and T_5) and c (T_1) at Kibeho site; a (T_2), b (T_3, T_5), ab (T_5) and c (T_1) at Kinigi site. The grand mean was 10.39t/ha at Kibeho site while it was 7.25 t/ha at Kinigi site. At both sites, localised placement and split application performed better than row banding and single application, respectively.

Small size tubers: at Kinigi, methods and timing of fertilizer application were highly significant ($P<0.001$) while at Kibeho methods and timing of fertilizer application were highly significant ($P<0.001$) and significant ($P<0.05$), respectively; the interaction between the two factors was not significant at both sites ($P>0.05$) (Appendix 15). However, higher small size tuber yields (4.86 t/ha) were obtained from the treatments which received split application, by localised placement, with 50% of the total fertilizer rate applied at planting and the remaining at 14DAE (F_2T_2);

[48] Tx: Timing of fertilizer application:/T1: 100% of fertilizer applied at planting time , T2: 50% and 50% of fertilizer applied at planting and weeding time respectively , T3: 75% and 25% of fertilizer applied at planting and weeding time respectively, T4: 50% and 50% of fertilizer applied at planting and earthing up time respectively and T5: 75% and 25% of fertilizer applied at planting and earthing up time respectively.

lower small size tuber yields (3.50 t/ha) were obtained from the treatments which received single application of the fertilizer by the row banding method (F_1T_1).

At the two sites, the treatment which received 50% of the total fertilizer rate at planting and the remaining at 14DAE (T_2) occupied the 1st place (4.03 t/ha and 4.28 t/ha at Kibeho site and Kinigi site, respectively) while the treatments which received single application of the total fertilizer rate at planting (T_1) occupied the last place (2.76 t/ha and 3.01 t/ha at Kibeho and Kinigi, respectively). Localised placement (4.02 t/ha and 4.04 t/ha at Kibeho and Kinigi, respectively) performed better, in both locations, than row banding (3.02 t/ha and 3.28 t/ha at Kibeho site and Kinigi site, respectively). Duncan's Multiple Range Test classified times of application in different groups: a (T_2, T_3, T_4 and T_5) and b (T_1) at Kibeho; a (T_2), b (T_3, T_4 and T_5) and c(T_1) at Kinigi. The grand mean was 3.55 t/ha at Kibeho while it was 3.66 t/ha at Kinigi. At both sites, localised placement and split application yielded more small size tuber yields than banding and single application, respectively.

The results are in agreement with the findings of Hensel and Locascio (1987) who conducted a research on" Effect of rates, form, and application date of nitrogen on growth of potatoes" and found significant effects of date and split application on yields; split application performed better than single application. The results also agree with the findings of Reiter *et al.* (2009) who recommended split application (three way-split or two way-split) of nitrogen fertilizer in order to maximize potato tuber yields. The results are consistent with the findings of Hochmuth and Cordasco (2000) who proved the performance of N and K fertilizers split application. For P, split application was recommended, by the same researchers, in case of water soluble fertilizer use. The results are in agreement with the findings of Zebarth *et al.* (2012) who found out the performance, in terms of potato tuber yield, of split application and localized fertilizer placement compared to single application and other forms of fertilizer placement, respectively. The study's results also agree with the findings of Askew (1992). The author recommended split application of N and K fertilizers on one hand and closer placement of N, P and K fertilizers to the proximity of crop root system on the other hand in order to maximize potato tuber yields.

The research's results are consistent with the findings of Hawkins (1954) who did a research on "Time, method of fertilizer application and placement of fertilizer for efficient production of potatoes in new England". He found that side placement of fertilizer resulted in more tuber yields than other methods of fertilizer application. The results are also in agrrement with the findings of Mohamood *et al.* (2002) who did a reserch whith the objective to compare different methods of fertilizer application vs broadcasting, placement and banding and found out the superiority of placement over banding and broadcating in terms of soil coverage and yields. The results aalso agrre with the findings of Tandon and Roy (2004) in terms of integrated nutrient management where they suggested split application of N and K fertilizers and side placement of P fertilizer for optimum fertilizer use efficiency and maximum yield.

The study's results are consistent with the findings of Zebarth *et al.* (2012) who recommended closer placement of N fertilizer to root system and its split application in case of potential leaching in order to optimize nutrient management and maximize tuber yields. The results agree with the findings of Zaag (1981) research. Focusing his research on soil fertility requirements for potato production, he recommended split application of N fertilizer in order to minimize its leaching loss, to optimize nutrient efficient use and maximize yield. The study's results are in agreement with the findings of Waterer and Heard (2003) who recommended split application of N, K (and even P if necessary) fertilizer and their closer placemen to crop root system in order to optimize fertilizer use efficiency and maximize potato tuber yield. Also Lang *et al.* (1999) focuse their research on "Potato nutrient management for central Washington", and recommended split application of N and K fertilizer and closer placement to crop root system of N, P and K fertilizer in order to optimize nutrient use efficiency and maximize potato tuber yield. However, the research results disagree with the findings of some researchers. This is the case for Khan *et al.* (2007) who did a research on" Evaluation of various methods of fertilizer application in potato (*Solanum tuberosum* L.)" and proved the superiority of banding over placement in terms of almost all growth and yield parameters.

Effect of N-P-K timing and methods of application on potato growth and development

One of the challenges of Irish potato production, as with any crop, is the efficient management of nitrogen fertilizers. N is the most limiting factor in crop production and is higher in concentration than all other mineral nutrients in most plants (Stark, 2000 and Westermann, 2005). In potatoes, N rivals only K in highest mineral concentration (Westermann, 2005). Potatoes are especially sensitive to N deficiencies and excesses (Stark, 2000). Excessive N fertilizer applied at or before tuberization can extend the vegetative growth period and delay tuber development, resulting in a lower tuber yields and diminished tuber quality (Stark, 2000 and Pack *et al.,* 2006). However, too much N applied later in the season can delay maturity of the tubers, reducing yields and adversely affecting tuber quality and skin set. Conversely, under-application of N at any point in the season can result in lower tuber yields and reduced profits (Stark, 2000 and Pack *et al.*, 2006).

Increase in yield depends on increase in the dry mass of plants which depends on the amount of photoassimilates fixed through photosynthesis (Lawlor, 1990). Solar radiation interception, water supply, CO_2 availability, air/soil temperature, and mineral nutrients are factors that determine the amount of photosynthesis (Kormondy, 1996). In this study, plants treated with split application and localized placement showed taller plants which normally should have high number of leaves, high canopy cover and high LAI (even if it has not been measured during the study but its trend can be predicted by simulation on the basis of measured parameters). These growth characteristics should result from a vigor root system well developed and properly established. Taller plants with a vigorous root system, high canopy cover and higher LAI should lead to higher photosynthesis rate resulting in good storage capacity, and then big and high number of tubers leading to high tuber yield.

The tuber yield increase resulted from stimulation of stolons branching, promotion of shoot growth of potatoes and tubers swelling. The timing of application of fertilizer (especially N and K) is an important factor in determining the rate of growth and yield of a plant. The key to plant growth and development depends on the establishment of vigorous and developed root system and a healthy large LAI that is durable through the productive phase, achieved through adequate N, P, K and water supply. In this study, taller plants, which normally should have high number of leaves, high canopy cover and probably greater LAI, were observed in potatoes that received split application of fertilizer through localized placement method. Hence, split application combined with localized placement of the fertilizer enabled a high interception of solar radiation, mainly due to the taller plants normally with high number of leaves, high canopy cover and greater photosynthetic surface area of the crop (LAI). This resulted in increased photosynthetic capacity and supply of the assimilates leading to increased growth.

The greater growth in split application and localized placement of fertilizer may have resulted into faster and balanced root growth, increase in bulking rate, high number of tubers and high tuber grades yield and high total tuber yield. Fast and balanced root growth enables faster shoot growth rates since there is greater capture of other nutrients resulting from increased root surface area of absorption. Apart from affecting root growth, increased growth may have led to more total dry matter accumulation and translocation into tubers, and hence, leading to high tuberisation and tuber dry mass yields in the potatoes treated with localized placement and split application (Gunasema and Harris, 1968). This led to big and high number of tubers and better yield in the concerned treatments. It has been suggested that split application of fertiliser leads to increased growth and hence improved yield over applying the fertiliser whole at planting (Kidin and Zamaraev, 1996) and the statement was confirmed by results of this study. In this study, potatoes that received split application (second portion) of fertilizer at 28DAE (T_4) didn't show the same performance (number of tubers per plant and even tuber yield) as the ones who received it at 14DAE (T_2). This suggests that the growth that occurred after the additional supply (at earthing up time) was mostly manifested in maintenance of vegetative phase with very little concomitant increase in tuber growth. Due to the additional supply of fertilizer at this second time, there was increase in growth to catch up the gap to other treatments but this was more manifested in vegetative than size/number of tubers and tuber yield; tuberization had already started. These results therefore show that potato growth, development and production will be improved most by fertilizer localised placement and split application but the additional supply being executed exactly fifteen days after emergence (or simply before thirty days after emergence).

Single application resulted in shorter plants which normally should have low number of leaves, low canopy cover, low LAI and root system less developed during major growth stages of the crop. The low canopy cover and LAI led to low interception of solar radiation and hence low photosynthetic capacity to support growth, development and maintenance of vegetative and yield parts. Consequently, these potatoes showed inferior heights, number of tubers per plant, tuber size and tuber yield. Addiscott *et al.* (1992) proved that the availability of applied N to the potato crop depends on the method of fertiliser application. He continued by saying that even if N is mobile and then its method of application shall have a little effect, under water stress conditions the effect should become significant. This was the case for the 1st days of our field experiment, the crop sometimes received little rainfall.

The performance of N, P and K fertilizer placement to the proximity of the crop root system (localized placement) over other methods of application have been supported by the findings of some other researchers: Jones and Jacobsen *(*2009), Roy *et al.* (2006), Alberta (2002), Lang *et al.* *(*1999), Jones and Jacobsen (2001) among others. The study's results, however, suggest that split application and localized placement of N-P-K with the additional fertilizer applied exactly fifteen days after emergence (or simply before thirty days counted from emergence) will improve growth, development, yield components and total tuber yield. Additional supply of the fertilizer applied late (after fifteen days following emegernce) only led to delayed growth and development at the expense of tuber initiation and bulking. Single application and banding method led to poor growth and development, low tuber yield components and low total tuber yield. Single application, late split application and banding may not be adapted for increased yields in potatoes.

Effect of N-P-K timing and methods of application on potato tuber yield components and total tuber yield

Increase in potato yield is mainly due to increase in number and size of the potato tubers (Kotsyuk, 1995). The number and size of tubers depend on the rate of tuber initiation and the amount of photoassimilates generated through photosynthesis. N has been shown to affect tuber initiation and the rate and amount of photosynthates (Kormondy, 1996; Salisbury and Ross, 1991). The study'results showed that both methods and time of application of N-P-K affected potato tuber number, tube grades and tuber yield. Localised placement and split application (early split application) had the highest number of tubers and the highest tuber yield while row banding and single application had the lowest values. The number of tubers per plant, tuber grades and tuber yield were affected by methods of fertilizer application. The results therefore, suggest that localized placement and banding had effect on tuber initiation and hence the number of tubers per plant and tuber size of these potatoes. This suggests that the observed differences in yield were explained by differences in both parameters, tuber number per plant and tuber size/weight. Although tuber weight per plant was not recorded in this experiment, it is likely to have been highest with potatoes that received localized placement.

High tuber yields may have resulted from high dry masses due to the accumulation of photoassimilates (photosynthates), that were high in these potato due to an appropriate establishment of a vigorous root system, taller plants and large canopy cover, and probably greater LAI as already discussed. In addition, it is more of the result of translocation of photoasssimilates towards the tubers than the shoots in these potatoes. The results of this study show that time of application of fertilizer affected potato number of tuber per plant, tuber size and tuber yield significantly. High number of tuber per plant, superior tuber grade and tuber yields were obtained in potatoes that had early split followed by late split and lastly single application of the fertilizer. As already discussed, early split application of N-P-K led to high rates of growth and development resulting in root system well developed, taller plants, high canopy cover and probably high number of leaves and great LAI.

The increase in root growth and development resulted in increase in both the number (tuber initiation) and size (bulking rate) of tubers. Higher growth (stem height-number of leaves-canopy cover and probably LAI) may have led to more total dry matter accumulation and translocation into tubers and most assimilates were channeled towards tuber growth than vegetative growth. Martin (1995) suggested that N supply increases the duration of tuber bulking and this may result in large sized potato tubers hence high yields. Phosphorus application affects crop growth by increasing radiation interception (over the whole season) or by increasing light use efficiency. The former is likely to be more important than the latter, therefore enhancing canopy growth becomes more important (Hakoomat and Muhammad, 2004). Similarly, Westermann and Kleinkopf (1985) reported that plant nutrient concentrations and uptake rates play a major role in maintaining a plant top which leads to increased tuber yields. Soltanpour and Cole (1978) found that proper application of N and P fertilizers increased leaf, stem and tuber growth rates and, consequently tuber yields.

Potassium is essential for photosynthesis, starch formation, and the translocation of sugars. It is also important in helping plants adapt to environmental stress (Havlin *et al*., 1999). The response to K^+ uptake by crops depends to a considerable extent on the level of N nutrition. Generally, the better the crop is supplied with N the greater the yield increase due to K supply (Havlin *et al*., 1999). In this study, early split application of NPK may have led to early tuber initiation. The tubers therefore, had a long bulking period resulting in high number of tuber per plant, large sized tubers and hence more tuber yield. Potatoes that received late split application had lower yields than that received early split application of N-P-K. It is possible that the later fast growth rate, late in the season, did not support increase in tuber number or sizes of the potatoes. This therefore, suggests that the late added N-P-K only supported more vegetative growth rather than tuber growth and size. It has been proved that establishment of a high LAI and leaf area duration early in the growth will increase the photosynthetic capacity and the amount of photosynthates produced and, consequently, greater production (Kormondy, 1996).

Conversely, a late establishment of the vegetative growth will lead to low photosynthesis hence low production. In this study, the potatoes which received late split application of N-P-K showed lower potato yields. This occurred since the plants had the fewest tubers per plant. It is therefore suggested that the potatoes receiving late additional N-P-K supports more vegetative growth than tuber growth. These potatoes therefore showed lower yields.

The method of application of N-P-K affected tuber number per plant, tuber size and tuber yield. The optimal result of localised placement is attributed to the fact that little or no fertilizer is wasted as all nutrients come in close contact with feeding roots, which are weak, shallow and less developed, and plant use those nutrients efficiently. Some wastage of fertilizer may take place in banding while some may be localized too far away from the root system. It is therefore concluded that localized placement method of application of N-P-K shall be adopted with early split application (50% of the rate applied at planting and 50% applied at 14DAE). It suggests that localized placement method of N-P-K with earl split application will improve yield and yield components of potatoes. Banding, single and late split applications don't lead to similar yield improvements in potato; they shall not be adopted for increasing yields in potatoes. It is possible that where N-P-K was applied through single application, the plants root system was not fully developed hence much of the applied fertilizer was not absorbed and stored in the plant system. More fertilizer was, therefore, lost through water erosion or leaching from the soil. In early split application of NPK, the crop had a well developed root system and therefore most of the applied fertilizer was absorbed into the plant system with a big portion not used in the growth but being stored in tuber tissues.

In this study, there were some differences between two locations in terms of yields and yield components. These differences between both locations could be attributed to weather difference between the sites besides other probable causes. This may due to the weather difference between the two locations in terms of rainfall (annual and seasonal average), daily temperatures and daily temperature ranges. At Kinigi site, both montly rainfall amount (consequently soil humidity) and daily temperature ranges were higher while daily and average temperatures were lower than the ones at Kibeho site. The number of tubers set per plant is greater at lower temperatures than at higher temperatures and cool night temperatures are important because they affect the accumulation of carbohydrates and dry matter in the tubers. At lower night temperatures, respiration is slowed, which enhances storage of starch in the tubers (Western potato council, 2003). Potatoes require a continuous supply of soil water along with adequate soil aeration. Yields are greatest when soil moisture is maintained above 65% of the available soil water capacity (Western potato council, 2003). All these mentioned weather factors are known to shorten vegetative growth rate, to stimulate tuber initiation, to increase photoassimilates translocation and storage rate, to lengthen tuber bulking period and then to lead to big and high number of tubers and great tuber yield (Western potato council, 2003).

Another factor that caused differences between the two locations is soil texture: it was sandy loam and silty clay loam at kinigi and Kibeho, respectively. It has been shown that well-drained soils with loamy sand to sandy loam textures are considered most suitable for potato production. These soils have an adequate capacity to retain water, provide sufficient aeration for root and tuber development and favourable conditions for planting and harvesting (Western potato council, 2003). Farmers are successfully producing potatoes on silt loam, sandy clay loam; silty clay loam and clay loam textural classes even though these soils are not considered ideal for potato production. These finer texture soils are prone to water erosion in undulating landscapes, poor to fair internal drainage and soil clod formation if tilled when wet. A soil that contains a large amount of clay (fine textured soil with more than 35% clay) becomes sticky when wet and lumpy when dry (Western Potato Council. 2003).

4.5 Correlation between selected agronomic parameters and potato tuber yields

The relationship between tuber yield and selected growth and yield component parameters was checked on basis of bar graphs (figures 4-7) analysis on one hand and on the other hand by correlation coefficient (r) analysis (tables11and Appendices 16-17). The selected growth parameters were stem height and canopy cover while the yield component considered parameter was the number of tubers per plant.

Refering to the main effect ot timing of fertilizer application, the bar graphs for both sites (figures 4-5), look like each other and relashionship between stem height, canopy cover, number of tubers per plant and tuber yield accross times of fertilizer application is constant. The constancy of the relationship shows that stem height, canopy cover and number of tubers per plant are directly proportional to tuber yield. The relashionship contancy also shows the high potential probability to predict accurately the dependent variable on the basis of independent variables.

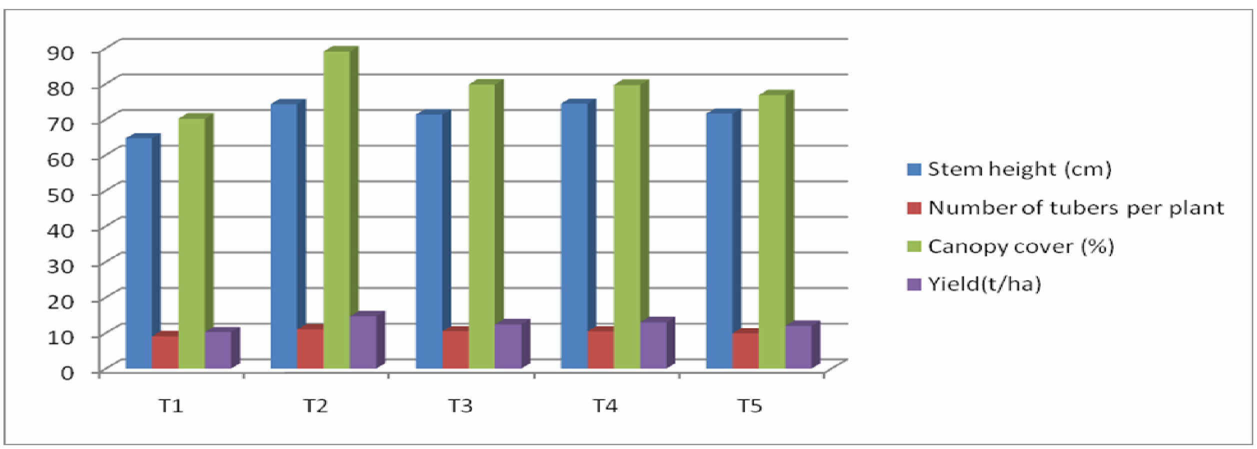

Figure 4: Relashionship between selected agronomic parameters and tuber yield across times of N-P-K (17-17-17) fertilizer application, Kibeho site

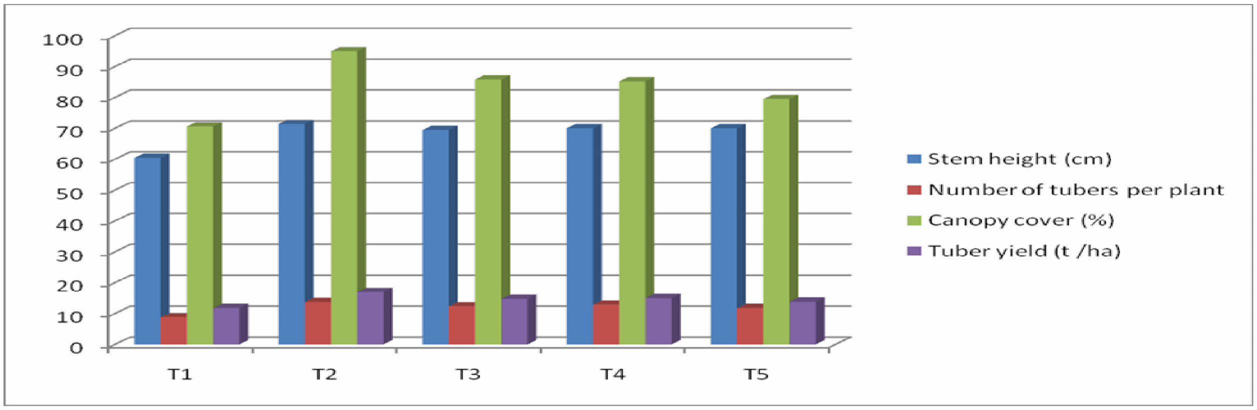

Figure 5: Relashionship between selected agronomic parameters and tuber yield across times of N-P-K (17-17-17) fertilizer application, Kinigi site

Refering to the effect of timing and methods of fertilizer application, the bar graphs for both sites, also look like each other and relashionship between stem height, canopy cover, number of tubers per plant and tuber yield across times and methods of fertilizer application is constant. The constancy of the relationship shows that stem height, canopy cover and number of tubers per plant are directly proportional to tuber yield. The relationship constancy also shows the high potential probability to predict accurately the dependent variable on the basis of independent variables.

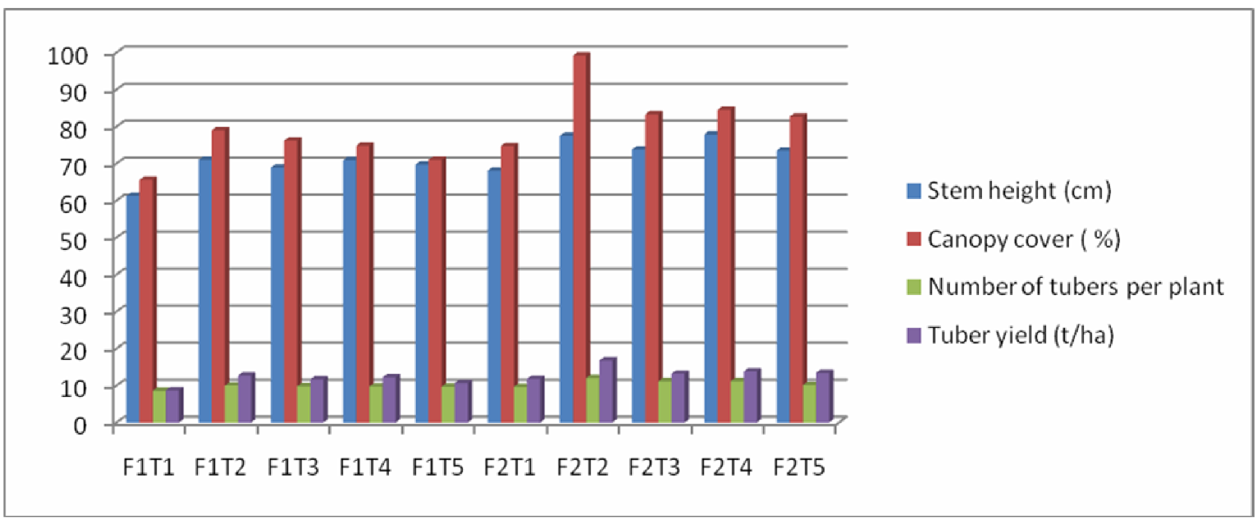

Figure 6: Relationship between selected agronomic parameters and tuber yield across times and methods ofN-P-K (17-17-17) fertilizer application, Kibeho site

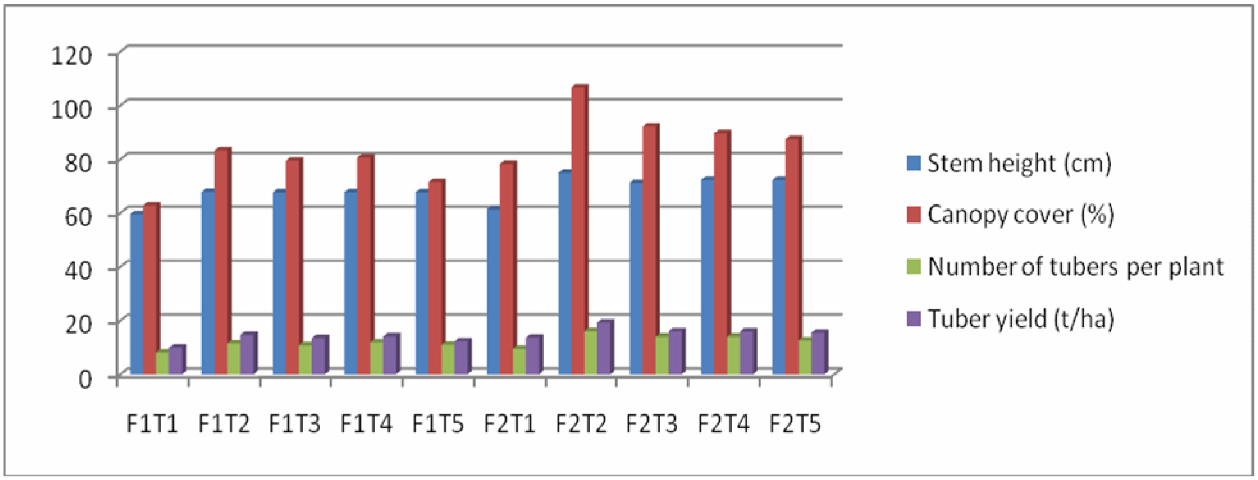

Figure 7: Relashionship between selected agronomic parameters and tuber yield across times and methods of N-P-K (17-17-17) fertilizer application, Kinigi site

At both sites, the correlation coefficients between selected agronomic parameters and tuber yield (Table 11) were significant ($r \geq 0.361$ and $r \geq 0.878$ in cases of effect of times and methods of fertilizer application and main effect of timing of fertilizer application, respectively). At Kibeho site and referring to the effect ot timing and methods of fertilizer application, the correlation coefficients between stem height, canopy cover, number of tubers per plant and tuber yield were 0.40, 0.97 and 0.49 while they were 0.71, 0.99 and 0.65 at Kinigi site, respectively. Concerning the main effect of timing of fertilizer application, the correlation coefficients between stem height, canopy cover, number of tubers per plant and tuber yield were 0.89, 0.98 and 0.96 at Kibeho site while they were 0.87, 0.99 and 0.96 at Kinigi site.The medium and high correlation coefficients indicate a significant dependence of dependent variable (tuber yield) on independent variables (stem height, canopy cover and number of tubers per plant) and the existing of linear relationship between these parameters. According to the study's results, tuber yield depends on stem height, canopy cover and number of tubers per plant among other inherent and environmental factors determining potato tuber yield.

Table 11: Correlation analysis, selected agronomic parameters to tuber yield

Sites	Treatment	Stem height	Canopy cover	Number of tubers per plant	Degree of freedom	Level of significance (P)	Significaa-nce
		Correlation coefficient (r) to tuber yield				0.05	
Kibeho	TxFx	0.405	0.979	0.497	28	0.361	Significant (r ≥0.361)
	Tx	0.897	0.988	0.966	3	0.878	Significant (r ≥0.878)
Kinigi	TxFx	0.713	0.997	0.652	28	0.361	Significant (r ≥0.361)
	Tx	0.878	0.995	0.960	3	0.878	Significant (r ≥0.878)

TxFx: effect of timing and methods of mineral fertilizer application

Tx: main effect of timing of mineral fertilizer application

Increase in yield depends on increase in the dry mass of plants which depends on the amount of photoassimilates fixed through photosynthesis (Lawlor, 1990). Solar radiation interception, water supply, CO_2 availability, air/soil temperature, and mineral nutrients are factors that determine the amount of photosynthesis (Kormondy, 1996). In this study, plants treated with split application and localized placement showed taller plants which should normally have more number of leaves, large canopy cover and high LAI. These growth characteristics should result from a vigorous root system well developed and properly established. Taller plants with a vigoousr root system, large canopy cover and high LAI should lead to high photosynthesis rate resulting in good storage capacity, and then big and high number of tubers leading to high tuber yield. The tuber yield increase resulted from stimulation of stolons branching, promotion of shoot growth of potatoes and tubers swelling.

The timing of application of fertilizer (especially N and K) is an important factor in determining the rate of growth and yield of a plant. The key to plant growth and development depends on the establishment of vigorous and developed root system and a healthy large LAI that is durable through the productive phase, achieved through adequate N-P-K and water supply (Gunasema and Harris, 1968). In this study, taller plants, which should normally have more number of leaves, large canopy cover and greater LAI, were observed in potatoes that received early split application of the fertilizer. Hence, early split application of the fertilizer enabled a high interception of solar radiation, mainly due to the taller plants which normally should have more number of leaves, large canopy cover and greater photosynthetic surface area of the crop (LAI). This resulted in increased photosynthetic capacity and supply of the assimilates leading to increased growth. The greater growth in early split application of the fertilizer may have resulted into faster and balanced root growth, increase in bulking rate, big and high number of tubers and the high tuber yield (Kotsyuk, 1995).

Fast and balanced root growth enables faster shoot growth rates since there is greater capture of other nutrients resulting from increased root surface area of absorption. Apart from affecting root growth, increased growth may have led to more total dry matter accumulation and translocation into tubers, and hence, leading to high tuberisation and tuber dry mass yields in the potatoes treated with split application (Gunasema and Harris, 1968). This led to big and high number of tubers and better tuber yield in the concerned treatments. It has been suggested that split application of fertiliser leads to increased growth and hence improved tuber yield over applying the fertiliser whole at planting (Kidin and Zamaraev, 1996) and the statement was confirmed by the results of this study. In this study potatoes treated with late split application of the fertilizer at earthing up time didn't show the same performance (number of tubers per plant and even tuber yield) as the ones who received the second fertilizer portion at weeding time. This suggests that the growth that occurred after the late additional supply (at earthing up time) was mostly manifested in maintenance of vegetative phase with very little concomitant increase in tuber growth. Due to the late additional supply of the fertilizer , there was increase in growth to catch up the gap to other treatments but this was more manifested in vegetative growth than size/number of tubers and tuber yield; tuberization had already started. Compared to other times of N-P-K application, split application with 50% of the total fertilizer rate applied at planting time and the remaining at 14DAE (T_2) was the optimal way to match fertilizer application with crop nutrients uptake and to synchronize nutrient availability with potato demand within time and over all crop growth and development phases.

Single application resulted in shorter plants which should normally have less number of leaves, narrow canopy cover, low LAI and root system less developed during major growth stages of the crop (Kotsyuk, 1995). A narrow canopy cover and LAI led to low interception of solar radiation and hence low photosynthetic capacity to support growth, development and maintenance of vegetative and yield parts. Consequently, these potatoes showed inferior heights, number of tubers, tuber size and tuber yield. Increase in potato yield is mainly due to increase in number and size of the potato tubers (Kotsyuk, 1995). The number and size of tubers depend on the rate of tuber initiation and the amount of photoassimilates generated through photosynthesis. High tuber yields may resulted from high dry masses due to the accumulation of photoassimilates, that were high in these potato due to an appropriate establishment of a strong root system, tall plants and large canopy cover, and probably greater LAI as already discussed.

Nitrogen is an essential nutrient for crop growth. The demand for nitrogen in the potato crop is relatively high. Nitrogen supply affects an array of physiological processes and morphological traits of the potato crop. These include (1) the rate of canopy development, (2) the rate of leaf appearance, the rate of individual leaf growth, final leaf size, and the life span of individual leaves, (3) the integral of light interception by the crop over time, (4) the rate of photosynthesis, (5) the number of lower and sympodial branches, and (6) the onset of tuberization, final tuber yield and final harvest index (Biemond & Vos, 1992; Ewing & Struik, 1992; Vos & Biemond,1992; Vos, 1995; Vos & MacKerron, 2000). Nitrogen supply may also affect quality aspects including tuber size distribution, tuber dry matter content, protein content, nitrate content and processing quality (Van Kempen *et al*., 1996).

No other major arable crop receives as large an application of phosphate fertilizers as potatoes and, therefore, the spotlight must fall on this crop as a candidate for more efficient P fertilizer use. Phosphorus application affects crop growth by increasing radiation interception (over the whole season) or by increasing light use efficiency. The former is likely to be more important than the latter, therefore enhancing canopy growth becomes more important. Similarly, Westermann and Kleinkopf (1985) reported that plant nutrient concentrations and uptake rates play a major role in maintaining a plant top which leads to increased tuber yields. Soltanpour and

Cole (1978) found that proper application of N and P fertilizers increased leaf, stem and tuber growth rates and, consequently yields.

Potassium is essential for photosynthesis, starch formation, and the translocation of sugars. It is also important in helping plants adapt to environmental stress (Havlin *et al*., 1999). The response to K^+ uptake by crops depends to a considerable extent on the level of N nutrition. Generally, the better the crop is supplied with N the greater the yield increase due to K supply. On the other hand, applied N is only fully utilized for crop production when K supply is adequate (Mengel and Kirkby, 1987). The potato (*Solanum tuberosum*) is a weather-sensitive crop with a wide variation among cultivars (Pashiardis,1987). The environment is one of the major variables affecting crop production in general but, in particular, potato crops. Successful potato crop production requires efficient use of climatic resources, namely solar radiation, temperature, water and mineral nutrients among many others. The growth of a potato crop that is well supplied with water and nutrients and free from pests and diseases is about proportional to its light absorption (Spitters, 1988; Van Delden, 2001).

The total biomass production and accumulation of potato cultivars are dependent on absorbed PAR, which directly proportional to the plant canopy cover (Spitters, 1988; Vos and Groenwold, 1989; Van Delden, 2001). Spitters (1988) indicated that tuber yield is determined by the fraction of total biomass that is partitioned to the tubers. Potato cultivar variation in yield can be analysed in terms of differences in cumulative light absorption, the efficiency with which the absorbed radiation is used for DM and the fraction of DM allocated to the desire plant organ (Pashiardis, 1988; Spitters, 1988; Van Delden, 2001).

According to MacKerron (1985), cultivars differences in conversion efficiency, have shown that for most of growing season, there is a linear relationship between TDM and integral of intercepted solar radiation. Hence the potential DM is manipulated using the conversion efficiency, which is the slope of the relationship. MacKerron (1985) further explained that the tuber potential yield could be estimated from the average value of the DM concentration, partitioned to both the top and tubers of the crop. Biomass production in crops, including potatoes, is dependent on photosynthate available, which is directly proportional to photosynthetic rate and the LAI of the crop (Tekalign and Hammes, 2005). High LAI usually indicates that the crop can intercept more solar radiation for photosynthetic activity. Potters and Jones (1977) also reported that the relationship between the crop leaf area and biomass accumulation is linear. The most important factor that affects rapid establishment of the crop canopy are genotype, seed environment, planting date and plant density, temperature and water stress conditions, and plant nutrient availability in soil. Drought and high temperatures affect leaf area development and its persistence. Leaf radiation absorption is governed by the rate of leaf appearance, leaf expansion, leaf size, geometry and direction (Pashiardis, 1988). Pashiardis (1988) further explains that in absence of water stress, temperature is the major environmental factor influencing the development of leaf surface. Thus, all previous interpretations and research findings prove how root system development, stem height and number-size of leaves, canopy cover, LAI, number of tubers per plant and Irish potato tuber yield are proportional and positively correlated; thus confirm our research outcomes.

CHAPTER 5

5.0 Conclusions and recommendations

5.1 Conclusions

Availability of sufficient quantity of plant nutrients on right time and in right place to root zon are among major parameters of nutrients management responsible for optimizing nutrient uptake and crop yield. In this regard, times and methods of mineral fertilizer application were considered as variables and their effects were evaluated on Irish potato selected growth, yield and yield component parameters during the research. The selected parameters were emergence rate, number of stems per plant, stem height, canopy cover, number of tubers per plant, tubers' grades yield and total tuber yield. The following conclusions merit to be drawn.

1. The main effects of timing and methods of fertilizer application on Irish potato growth and tuber yield were significant on all growth and tuber yield parameters except emergence rate and number of stems per plant while the interaction between both factors didn't show significant effect on any Irish potato growth or yield parameter.
2. Regarding times of fertilizer application, split application performed better than single application in general, and T_2 (application of 50% of the fertilizer rate at planting time and the remaining at 14DAE) and T_1 (application of the total fertilizer rate at planting time) were found to be the best and last performing treatments, respectively. Concerning methods of fertilizer application, localised placement performed better than row banding. The correlation coefficients between stem height, canopy cover, number of tubers per plant and tuber yield were positive and significant, showing a linear relationship and significant dependence between those parameters and tuber yield.
3. Timing, methods of mineral fertilizer application, and even their interaction didn't show a significant effect on any selected soil chemical properties, but all treatments combined with farm yard manure under blanket application increased soil reaction, organic carbon, nutrient concentrations and CEC, improved soil nutrients status and fertility in general and thus enhanced better Irish potato growth and tuber yields. Application of organic fertilizer plus mineral fertilizers, in accordance with proper timing and placement application, as integrated plant nutrient management, improved soil fertility and increased crop production per unit area through improvement of nutrient availability.

5.2 Recommendations

Based on the research findings, with the aim of maximizing their reliability, validity, accuracy, credibility and generalizability on one hand, and contributing to narrow the increasing gap between Irish potato huge market demand and skeletal farmers'supply on the other hand, the following recommendations can be formulated:

1. The current results may not allow us to draw last definitive conclusion because there are some factors (weather, soil properties, farming practices and their interactions) which may have affected the research findings. Several similar studies should be conducted, at different locations, within different Irish potato production agroecological zones and during different seasons, in Rwanda with the aim of collecting reliable data on the effect of timing and methods of mineral fertilizer application on Irish potato growth, yield components and tuber yield. Moreover, it may be better to define the research and set the field experiment in appropriate way to find out individual effects of organic and inorganic inputs .
2. Making profit is the ultimate objective of any business maker, including the one involved in Irish potato production. As profit is the 1^{st} driver for any decision maker wanting to start or fund Irish potato production project, this one must be insured for not only technical feasibility but also the economic one. The research was limited on the 1^{st} feasibility aspect but it is really of great importance to recommend undertaking a similar study placing financial and/or economic analysis of the research project on the head of the objectives array. The questioned analysis should put a monetary value on costs and benefits and measure the overall desirability of the research project in financial terms and indicate the superiority of a single treatment-approach over others that may be equally feasible in a technical sense. It should compare costs with benefits and determine which among alternative treatments have an acceptable and superior return.
3. In light of this research work, we recommend Irish potato producers of the study areas or others working in almost the same conditions, to apply 50% of the N-P-K (17-17-17) recommended rate at planting and 50% at 14DAE (T_2) using localized placement method (F_2) as the equivalent treatment, combined with FYM under blanket application in order to enhance Irish potato performance.

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APPENDICES

Appendix 1: Analysis of Variance for emergence rate

Analysis of variance for emergence rate, Kibeho site (S1)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	33.87	16.93	1.67		
Block.*Units* stratum						
Methods(**F_X**)	1	16.13	16.13	1.59	0.223	
Timing **(T_x)**	4	16.80	4.20	0.42	0.796	
Methods.Timing	4	12.53	3.13	0.31	0.868	
Residual	18	182.13	10.12			
Total	29	261.47				
l.s.d.	F_X: 2.440	T_x: 3.858		F_x*T_x: 5.457		CV(%): 3.3

Analysis of Variance for emergence rate, Kinigi site (S2)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	48.267	24.133	6.54		
Block.*Units* stratum						
Methods	1	4.800	4.800	1.30	0.269	
Timing	4	4.533	1.133	0.31	0.869	
Methods.Timing	4	1.867	0.467	0.13	0.971	
Residual	18	66.400	3.689			
Total	29	125.867				
l.s.d.	F_X:1.473	T_x: 2.330		F_x*T_x: 3.295		CV(%): 2.0

Appendix 2. Analysis of variance for number of primary shoots per plant 7DAE

Analysis of Variance for number of primary shoots per plant 7DAE**,** Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	0.4847	0.2423	2.22		
Block.*Units* stratum						
Methods	1	0.4083	0.4083	3.73	0.069	
Timing	4	0.3113	0.0778	0.71	0.595	
Methods.Timing	4	0.1767	0.0442	0.40	0.803	
Residual	18	1.9687	0.1094			
Total	29	3.3497				
l.s.d.	F_X:0.2537	T_x: 0.4011		F_x*T_x: 0.5673		CV(%): 15.8

Analysis of variance for number of primary shoots per plant 7DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	0.91267	0.45633	8.32		
Block.*Units* stratum						
Methods	1	0.03333	0.03333	0.61	0.446	
Timing	4	0.24467	0.06117	1.12	0.380	
Methods.Timing	4	0.11667	0.02917	0.53	0.714	
Residual	18	0.98733	0.05485			
Total	29	2.29467				
l.s.d.	F_X: 0.1797	T_x: 0.2841	F_x*T_x: 0.4018			CV(%):10.2

Appendix 3: . Analysis of variance for number of primary shoots per plant 14DAE

Analysis of variance for number of primary shoots per plant 14DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	0.36867	0.18433	2.92		
Block.*Units* stratum						
Methods	1	0.19200	0.19200	3.04	0.098	
Timing	4	0.20800	0.05200	0.82	0.528	
Methods.Timing	4	0.06800	0.01700	0.27	0.894	
Residual	18	1.13800	0.06322			
Total	29	1.97467				
l.s.d.	F_X: 0.1929	T_x: 0.3050	F_x*T_x:0.4313			CV(%):10.5

Analysis of variance for number of primary shoots per plant14DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	1.26467	0.63233	8.97		
Block.*Units* stratum						
Methods	1	0.06533	0.06533	0.93	0.348	
Timing	4	0.25333	0.06333	0.90	0.485	
Methods.Timing	4	0.25467	0.06367	0.90	0.483	
Residual	18	1.26867	0.07048			
Total	29	3.10667				
l.s.d.	F_X:0.2037	T_x: 0.3220	F_x*T_x: 0.4554			CV(%):10.3

Appendix 4: . Analysis of variance for number of primary shoots per plant 21DAE

Analysis of variance for number of primary shoots per plant 21DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	2.75267	1.37633	22.37		
Block.*Units* stratum						
Methods	1	0.16133	0.16133	2.62	0.123	
Timing	4	0.17467	0.04367	0.71	0.596	
Methods.Timing	4	0.11867	0.02967	0.48	0.749	
Residual	18	1.10733	0.06152			
Total	29	4.31467				
l.s.d.	F_X:0.1903	T_x:0.3009	F_x*T_x: 0.4255			CV(%):8.2

Analysis of variance for number of primary shoots per plant 21DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block stratum	2	2.20867	1.10433	25.12		
Block.*Units* stratum						
Methods	1	0.02133	0.02133	0.49	0.495	
Timing	4	0.15200	0.03800	0.86	0.504	
Methods.Timing	4	0.16533	0.04133	0.94	0.463	
Residual	18	0.79133	0.04396			
Total	29	3.33867				
l.s.d.	F_X:0.1609	T_x: 0.2543	F_x*T_x: 0.3597			CV(%):12.2

Appendix 5: Analysis of variance for number of primary shoots per plant 28DAE

Analysis of variance for number of primary shoots per plant 28DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	7.72067	3.86033	84.81	
Block.*Units* stratum					
Timing	4	0.12867	0.03217	0.71	0.598
Methods	1	0.02700	0.02700	0.59	0.451
Timing.Methods	4	0.19800	0.04950	1.09	0.392
Residual	18	0.81933	0.04552		
Total	29	8.89367			
l.s.d.	F_X: 0.1392	T_x:0.2201	F_x*T_x:0.3113		CV(%):5.5

Analysis of variance for number of primary shoots per plant 28DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.94600	0.97300	18.49	
Block.*Units* stratum					
Methods	1	0.01633	0.01633	0.31	0.584
Timing	4	0.17533	0.04383	0.83	0.522
Methods.Timing	4	0.22200	0.05550	1.05	0.407
Residual	18	0.94733	0.05263		
Total	29	3.30700			
l.s.d.	F_X: 0.1760	T_x: 0.2783	F_x*T_x: 0.3935		CV(%):8.2

Appendix 6: Analysis of variance for number of primary shoots per plant 35DAE

Analysis of variance for number of primary shoots per plant 35DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	4.94067	2.47033	75.03	
Block.*Units* stratum					
Methods	1	0.01633	0.01633	0.50	0.490
Timing	4	0.08867	0.02217	0.67	0.619
Methods.Timing	4	0.13533	0.03383	1.03	0.420
Residual	18	0.59267	0.03293		
Total	29	5.77367			
l.s.d.	F_X:0.2588	T_x:0.1637	F_x*T_x:0.3660		CV(%):6.4

Analysis of variance for number of primary shoots per plant 35DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.73600	0.86800	19.27	
Block.*Units* stratum					
Methods	1	0.01633	0.01633	0.36	0.555
Timing	4	0.07533	0.01883	0.42	0.793
Methods.Timing	4	0.16867	0.04217	0.94	0.465
Residual	18	0.81067	0.04504		
Total	29	2.80700			
l.s.d.	F_X:0.1628	T_x: 0.2574	F_x*T_x: 0.3640		CV(%):7.6

Appendix 7: Analysis of variance for stem height 14DAE

Analysis of Variance for stem height 14DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	16.595	8.297	5.91	
Block.*Units* stratum					
Methods	1	31.827	31.827	22.66	<.001
Timing	4	8.861	2.215	1.58	0.223
Methods.Timing	4	0.348	0.087	0.06	0.992
Residual	18	25.279	1.404		
Total	29	82.910			
l.s.d.		F_X:0.909	T_x:1.437	F_x*T_x:2.033	CV(%):7.8

Analysis of Variance for stem height 14DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	17.525	8.762	6.31	
Block.*Units* stratum					
Methods	1	31.621	31.621	22.77	<.001
Timing	4	8.915	2.229	1.60	0.216
Methods.Timing	4	0.355	0.089	0.06	0.992
Residual	18	25.002	1.389		
Total	29	83.419			
l.s.d.		F_X: 0.904	T_x: 1.430	F_x*T_x: 2.022	CV(%):9.0

Appendix 8: Analysis of variance for stem height 28DAE

Analysis of Variance for stem height 28DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	39.385	19.692	5.75	
Block.*Units* stratum					
Methods	1	131.880	131.880	38.51	<.001
Timing	4	23.765	5.941	1.74	0.186
Methods.Timing	4	25.725	6.431	1.88	0.158
Residual	18	61.635	3.424		
Total	29	282.390			
l.s.d.		F_X: 1.420	T_x: 2.245	F_x*T_x:3.174	CV(%):6.0

Analysis of Variance for stem height 28DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	10.341	5.170	1.48	
Block.*Units* stratum					
Methods	1	128.547	128.547	36.70	<.001
Timing	4	6.399	1.600	0.46	0.766
Methods.Timing	4	8.535	2.134	0.61	0.661
Residual	18	63.053	3.503		
Total	29	216.874			
l.s.d.		F_X: 1.436	T_x: 2.270	F_x*T_x:3.211	CV(%):7.6

Appendix 9: Analysis of variance for stem height 42DAE

Analysis of Variance for stem height 42DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	75.95	37.97	2.39	
Block.*Units* stratum					
Methods	1	144.76	144.76	9.11	0.007
Timing	4	475.63	118.91	7.49	<.001
Methods.Timing	4	65.74	16.44	1.03	0.417
Residual	18	285.94	15.89		
Total	29	1048.02			

l.s.d. F_X:3.058 T_x:4.835 F_x*T_x:6.837 CV(%):7.0

Analysis of Variance for stem height 42DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	76.17	38.08	2.38	
Block.*Units* stratum					
Methods	1	140.83	140.83	8.81	0.008
Timing	4	472.06	118.02	7.39	0.001
Methods.Timing	4	66.56	16.64	1.04	0.413
Residual	18	287.60	15.98		
Total	29	1043.23			

l.s.d. F_X: 3.066 T_x: 4.849 F_x*T_x:6.857 CV(%):7.7

Appendix 10: Analysis of variance for stem height 56DAE

Analysis of Variance for stem height 56DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	80.40	40.20	1.37	
Block.*Units* stratum					
Methods	1	263.44	263.44	8.97	0.008
Timing	4	363.10	90.78	3.09	0.042
Methods.Timing	4	14.33	3.58	0.12	0.973
Residual	18	528.44	29.36		
Total	29	1249.71			

l.s.d. F_X:4.157 T_x: 6.572 F_x*T_x:9.294 CV(%):7.9

Analysis of Variance for stem height 56DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	80.24	40.12	1.37	
Block.*Units* stratum					
Methods	1	264.03	264.03	9.03	0.008
Timing	4	359.87	89.97	3.08	0.043
Methods.Timing	4	15.96	3.99	0.14	0.967
Residual	18	526.02	29.22		
Total	29	1246.13			

l.s.d. F_X: 4.147 T_x: 6.557 F_x*T_x:9.273 CV(%):8.4

Appendix 11: Analysis of variance for stem height 70DAE

Analysis of Variance for stem height 70DAE, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	77.15	38.57	1.30	
Block.*Units* stratum					
Methods	1	251.14	251.14	8.45	0.009
Timing	4	374.90	93.73	3.15	0.040
Methods.Timing	4	11.72	2.93	0.10	0.982
Residual	18	534.84	29.71		
Total	29	1249.75			
l.s.d.	F_X:4.182	T_x: 6.612	F_x*T_x: 9.351		CV(%):7.7

Analysis of Variance for stem height 70DAE, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	116.42	58.21	2.23	
Block.*Units* stratum					
Methods	1	142.57	142.57	5.47	0.031
Timing	4	469.38	117.34	4.50	0.011
Methods.Timing	4	21.84	5.46	0.21	0.930
Residual	18	468.88	26.05		
Total	29	1219.09			
l.s.d.	F_X: 3.915	T_x:6.191	F_x*T_x:8.755		CV(%):7.5

Appendix 12: Analysis of variance for canopy cover (%)

Analysis of variance for canopy cover, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	875.22	437.61	8.95	
Block.*Units* stratum					
Methods	1	999.94	999.94	20.46	<.001
Timing	4	1114.36	278.59	5.70	0.004
Methods.Timing	4	155.05	38.76	0.79	0.545
Residual	18	879.79	48.88		
Total	29	4024.36			
l.s.d.	F_X: 5.36	T_x:8.48	F_x*T_x:11.99		CV(%):8.8

Analysis of variance for canopy cover, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1104.82	552.41	8.47	
Block.*Units* stratum					
Methods	1	1755.67	1755.67	26.92	<.001
Timing	4	1937.47	484.37	7.43	0.001
Methods.Timing	4	167.53	41.88	0.64	0.639
Residual	18	1173.85	65.21		
Total	29	6139.34			
l.s.d.	F_X: 6.20	T_x:9.801	F_x*T_x:13.85		CV(%):9.7

Appendix 13: Analysis of variance for number of tubers per plant

Analysis of Variance for number of tubers per plant, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.5247	1.2623	1.91	
Block.*Units* stratum					
Methods	1	12.0333	12.0333	18.20	<.001
Timing	4	12.5987	3.1497	4.76	0.008
Methods.Timing	4	2.0400	0.5100	0.77	0.558
Residual	18	11.9020	0.6612		
Total	29	41.0987			

l.s.d. F_X: 0.624 T_x: 0.986 F_x*T_x:1.395 CV(%):8.0

Analysis of Variance for number of tubers per plant, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3.354	1.677	0.74	
Block.*Units* stratum					
Methods	1	49.665	49.665	21.85	<.001
Timing	4	85.969	21.492	9.45	<.001
Methods.Timing	4	10.325	2.581	1.14	0.371
Residual	18	40.919	2.273		
Total	29	190.232			

l.s.d. F_X: 1.157 T_x:1.829 F_x*T_x:2.586 CV(%):12.6

Appendix 14: Analysis of variance for total tuber yield

Analysis of Variance for total tuber yield, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	32.561	16.280	8.40	
Block.*Units* stratum					
Methods	1	50.960	50.960	26.29	<.001
Timing	4	62.685	15.671	8.08	<.001
Methods.Timing	4	7.111	1.778	0.92	0.475
Residual	18	34.893	1.938		
Total	29	188.210			

l.s.d. F_X:1.068 T_x:1.689 F_x*T_x:2.388 CV(%):11.1

Analysis of Variance for total tuber yield, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	44.193	22.096	8.47	
Block.*Units* stratum					
Methods	1	75.843	75.843	29.07	<.001
Timing	4	84.995	21.249	8.15	<.001
Methods.Timing	4	7.205	1.801	0.69	0.608
Residual	18	46.954	2.609		
Total	29	259.190			

l.s.d. F_X: 1.239 T_x:1.959 F_x*T_x: 2.771 CV(%):11.1

Appendix 15: Analysis of variance for tuber yield grades

Analysis of Variance for big size tuber yield, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.9120	1.4560	8.43	
Block.*Units* stratum					
Methods	1	4.8803	4.8803	28.26	<.001
Timing	4	5.6987	1.4247	8.25	<.001
Methods.Timing	4	0.3880	0.0970	0.56	0.693
Residual	18	3.1080	0.1727		
Total	29	16.9870			
l.s.d.	F_X: 0.3188	T_x:0.5040	F_x*T_x:0.7128		CV(%):11.6

Analysis of Variance for medium size tuber yield, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	18.269	9.134	8.16	
Block.*Units* stratum					
Methods	1	28.421	28.421	25.38	<.001
Timing	4	35.291	8.823	7.88	<.001
Methods.Timing	4	4.235	1.059	0.95	0.461
Residual	18	20.158	1.120		
Total	29	106.375			
l.s.d.	F_X:0.812	T_x:1.284	F_x*T_x:1.815		CV(%):10.2

Analysis of Variance for medium size tuber yield, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	10.3920	5.1960	7.64	
Block.*Units* stratum					
Methods	1	19.6830	19.6830	28.93	<.001
Timing	4	21.2167	5.3042	7.80	<.001
Methods.Timing	4	1.6353	0.4088	0.60	0.667
Residual	18	12.2480	0.6804		
Total	29	65.1750			
l.s.d.	F_X: 0.633	T_x:1.001	F_x*T_x:1.415		CV(%):11.4

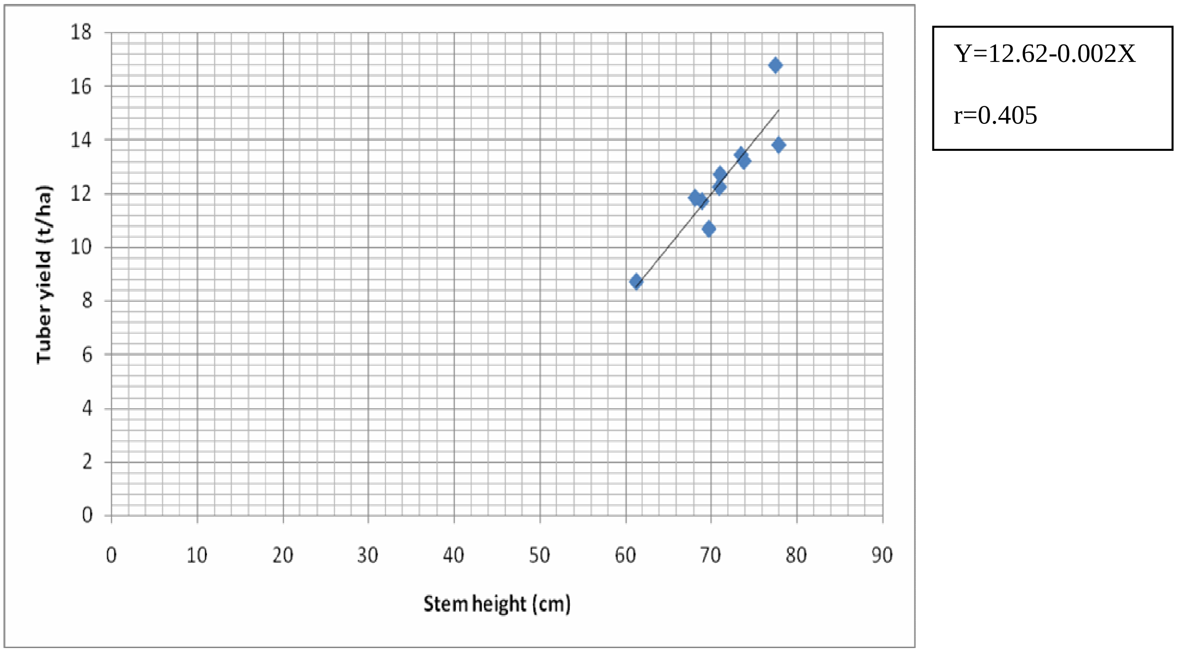
Analysis of Variance for small size tuber yield, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.2647	0.6323	2.55	
Block.*Units* stratum					
Methods	1	6.6270	6.6270	26.77	<.001
Timing	4	5.5187	1.3797	5.57	0.004
Methods.Timing	4	2.1680	0.5420	2.19	0.111
Residual	18	4.4553	0.2475		
Total	29	20.0337			
l.s.d.	F_X: 0.3817	T_x:0.6035	F_x*T_x:0.8534		CV(%):14.0

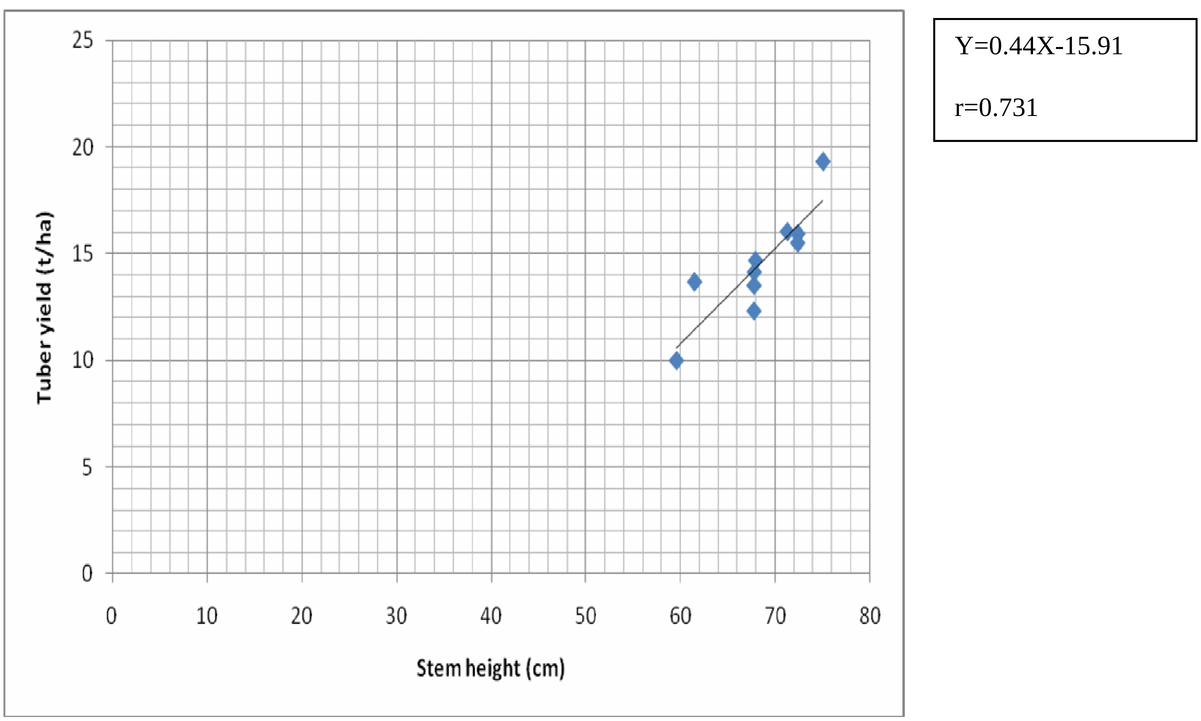
Analysis of Variance for small size tuber yield, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.8887	1.4443	9.12	
Block.*Units* stratum					
Methods	1	4.3320	4.3320	27.35	<.001
Timing	4	5.0367	1.2592	7.95	<.001
Methods.Timing	4	0.6380	0.1595	1.01	0.430
Residual	18	2.8513	0.1584		
Total	29	15.7467			
l.s.d.	F_X: 0.3053	T_x:0.4828	F_x*T_x: 0.6827		CV(%):10.9

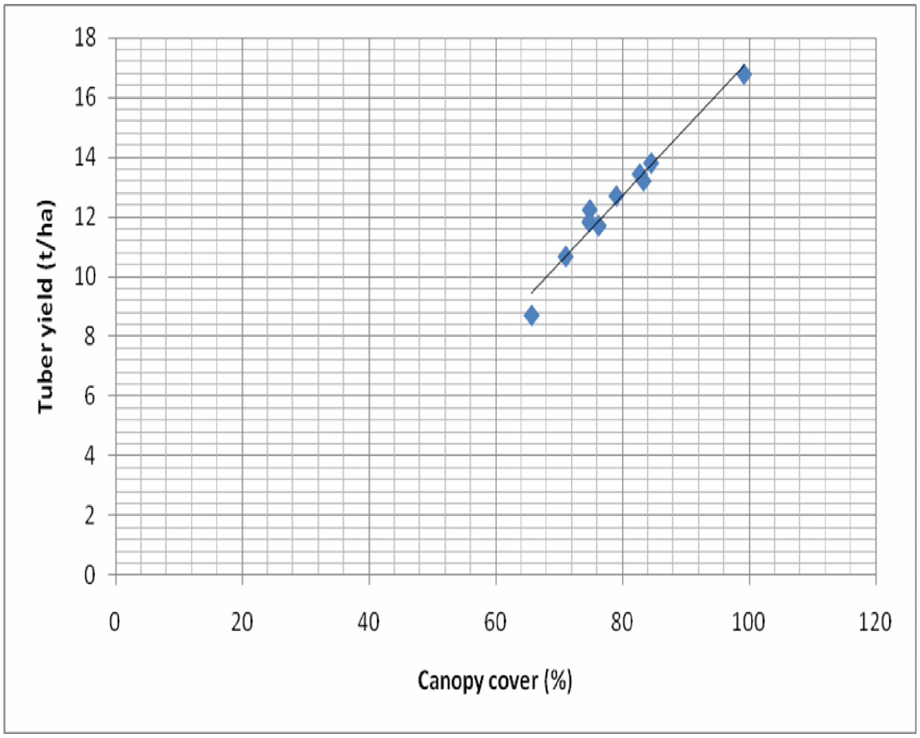
Appendix 16: Correlation between selected agronomic parameters and potato tuber yield (effect of both factors)



Correlation between stem height and tuber yield, Kibeho site



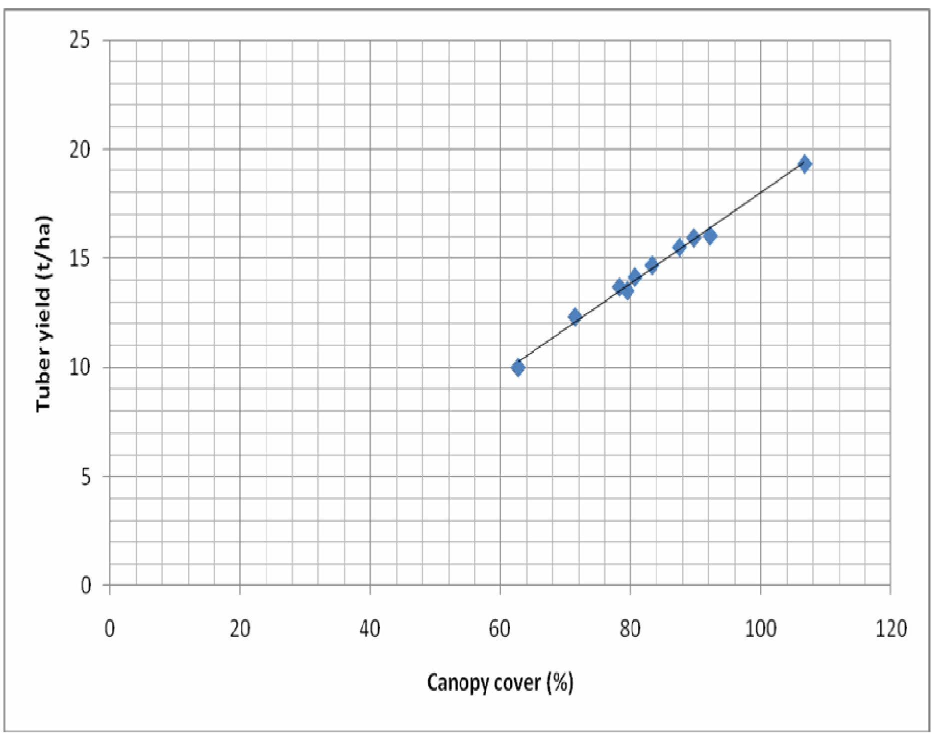
Correlation between stem height and tuber yield, Kinigi site



Y=0.22X-5.41

r=0.979

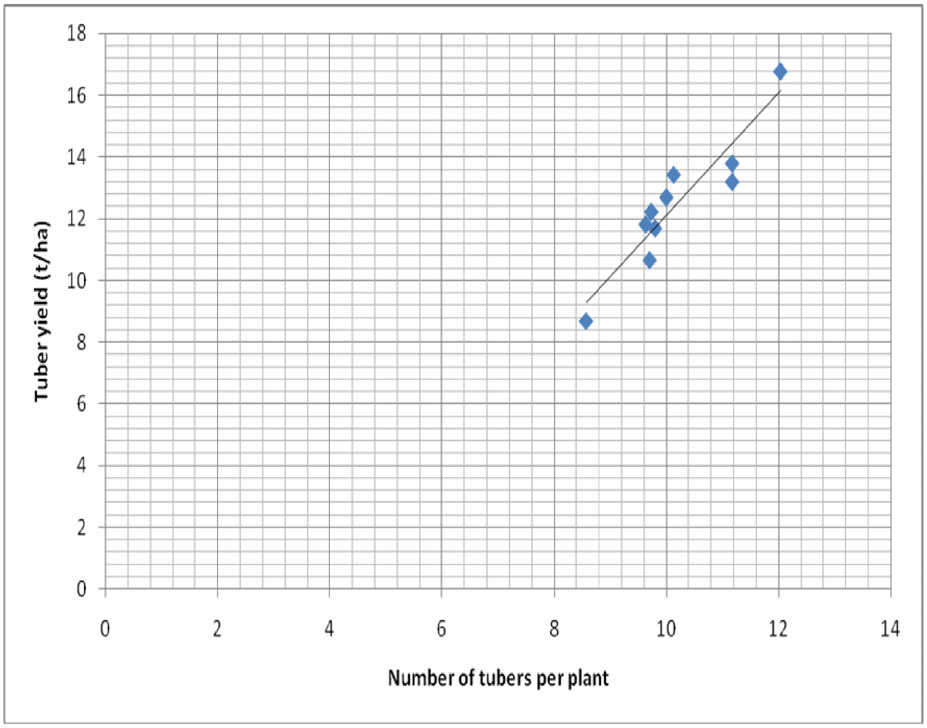
Correlation between canopy cover (%) and tuber yield, Kibeho site



Y=0.21X-2.75

r=0.997

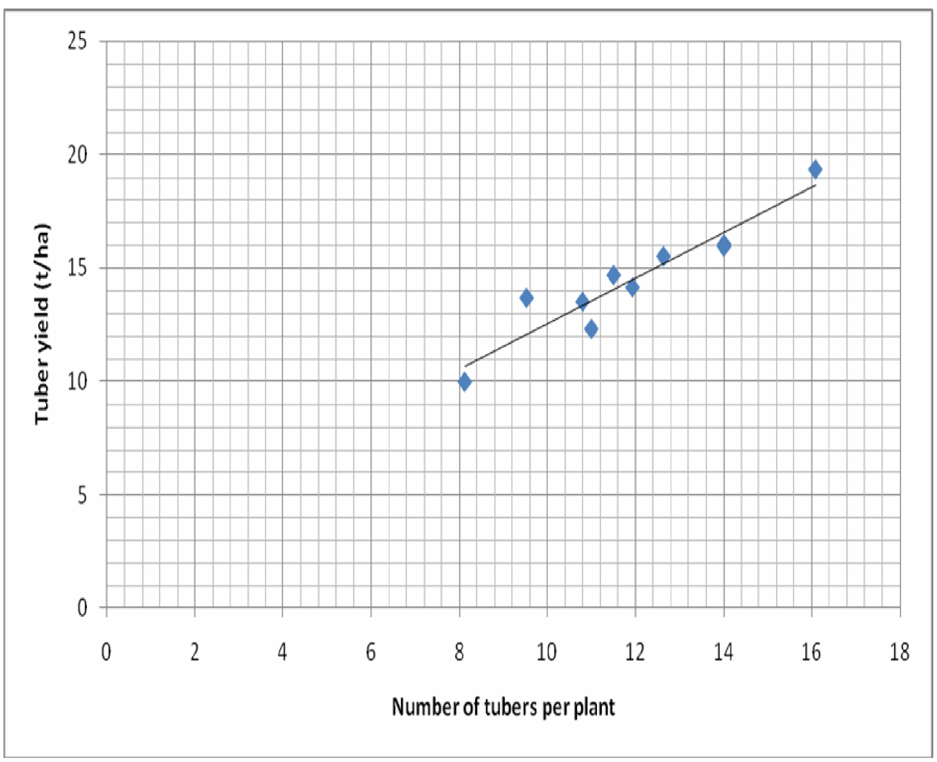
Correlation between canopy cover (%) and tuber yield, Kinigi site



Y=1.98X-7.67

r=0.497

Correlation between number of tubers per plant and tuber yield, Kibeho site

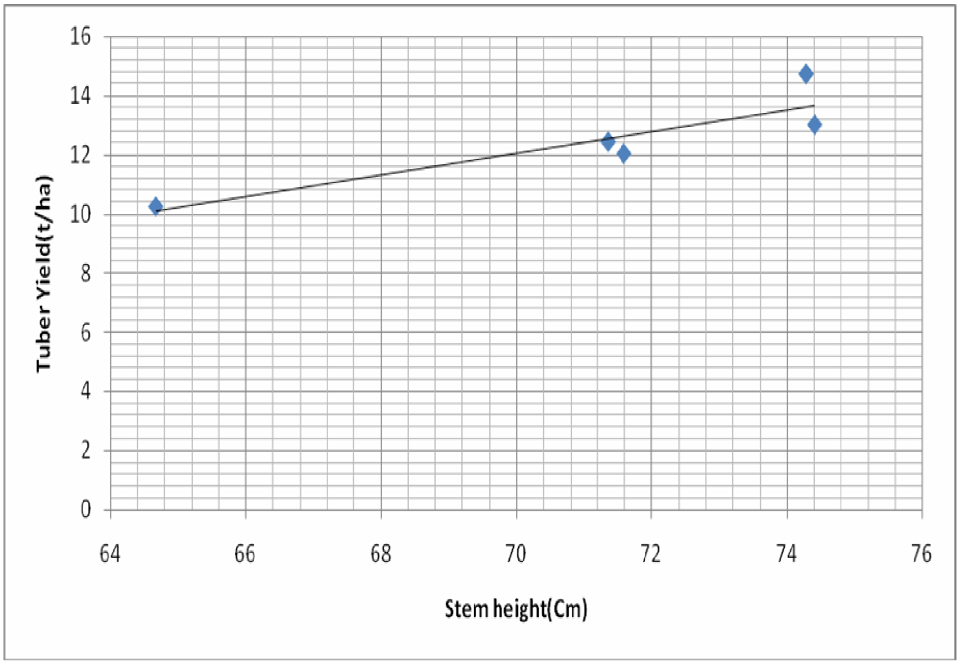


Y=x+2.44

r=0.652

Correlation between number of tubers per plant and tuber yield, Kinigi site

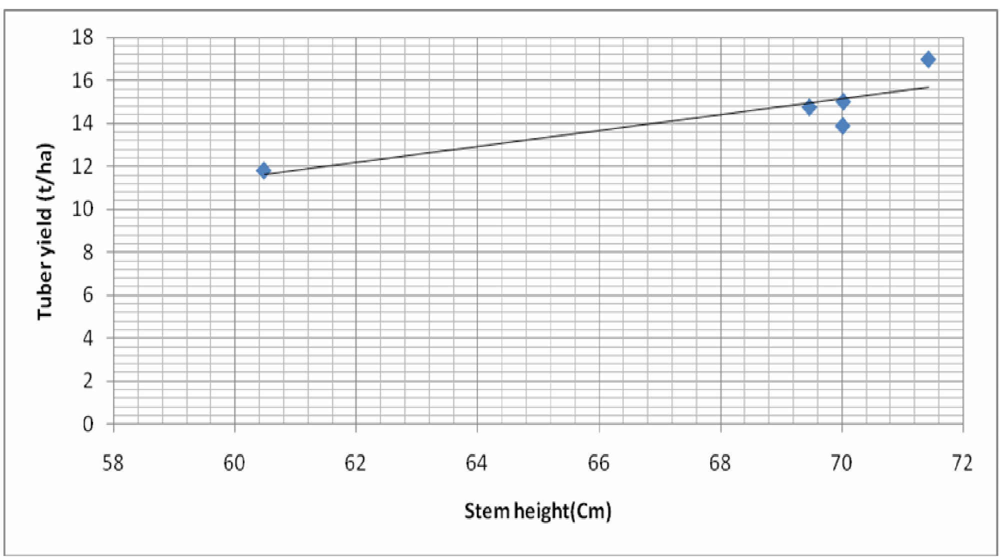
Appendix 17: Correlation between selected agronomic parameters and potato tuber yield (main effect of timing of fertilizer application)



Y=0.366X-13.61

r=0.897

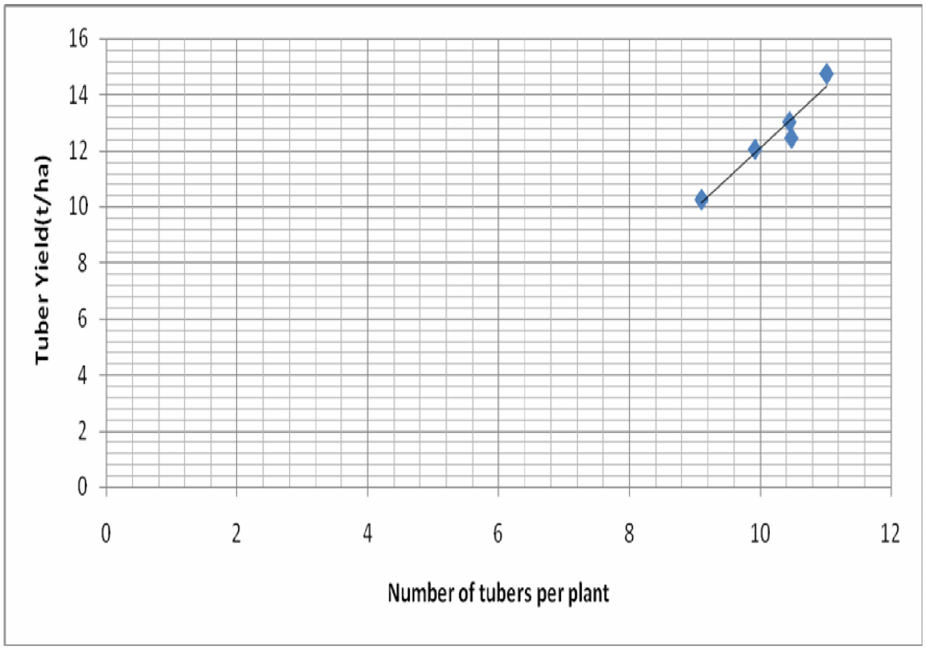
Correlation between stem height and tuber yield, Kibeho site



Y=0.370X-10.783

r=0.878

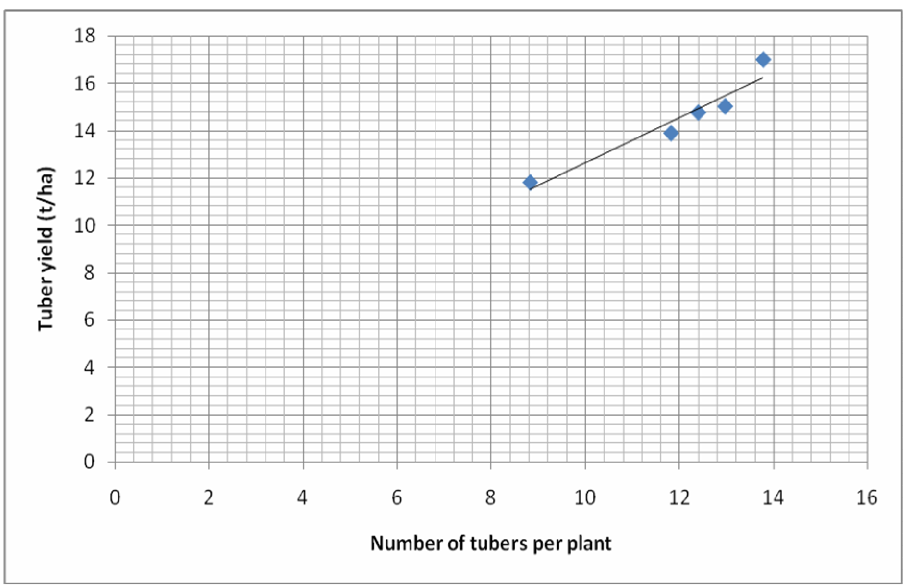
Correlation between stem height and tuber yield, Kinigi site



Y=2.15X-9.44

r=0.988

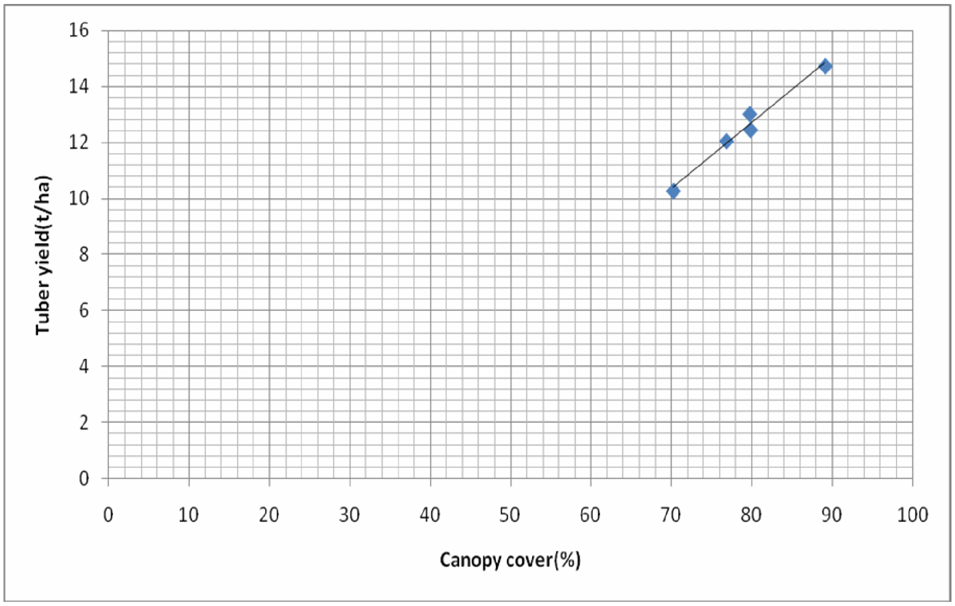
Correlation between number of tubers per plant and tuber yield, Kibeho site



Y=0.953X+3.099

r=0.995

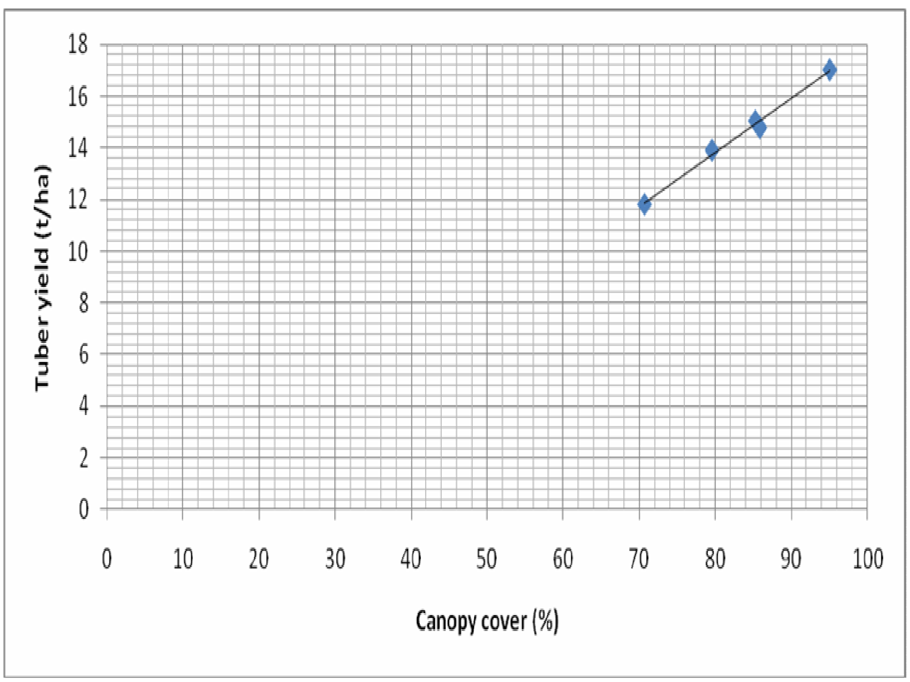
Correlation between number of tubers per plant and tuber yield, Kinigi site



Y=0.234x-6.05

r=0.966

Correlation between canopy cover and tuber yield, Kibeho site



Y=0.208-2.806

r=0.960

Correlation between canopy cover and tuber yield, Kinigi site

Appendix 18: Analysis of variance for soil pH before harvesting

Analysis of variance for soil pH, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.64951	0.32475	5.53	
Block.*Units* stratum					
Methods	1	0.04226	0.04226	0.72	0.407
Timing	4	0.16269	0.04067	0.69	0.607
Methods.Timing	4	0.01158	0.00289	0.05	0.995
Residual	18	1.05715	0.05873		
Total	29	1.92319			

l.s.d. F_X: 0. 0.1859 T_x : 0.2940: F_x*T_x: 0.4157 CV(%):4.1

Analysis of variance for soil pH, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.165420	0.082710	11.10	
Block.*Units* stratum					
Methods	1	0.008003	0.008003	1.07	0.314
Timing	4	0.002113	0.000528	0.07	0.990
Methods.Timing	4	0.006380	0.001595	0.21	0.927
Residual	18	0.134113	0.007451		
Total	29	0.316030			

l.s.d. F_X: **0.0662**. T_x: **0.1047** F_x*T_x: **0.1481** CV(%): 1.5

Appendix 19: Analysis of variance for soil organic carbon before harvesting

Analysis of variance for organic Carbon, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	11.0199	5.5099	14.31	
Block.*Units* stratum					
Methods	1	0.6483	0.6483	1.68	0.211
Timing	4	3.1180	0.7795	2.02	0.134
Methods.Timing	4	0.1982	0.0496	0.13	0.970
Residual	18	6.9300	0.3850		
Total	29	21.9143			

l.s.d. F_X: 0.476. T_x: : 0.753: F_x*Tx : 1.064 CV(%):8.7

Analysis of variance for organic Carbon, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.0167	0.0083	0.02	
Block.*Units* stratum					
Methods	1	1.0083	1.0083	2.02	0.172
Timing	4	1.1333	0.2833	0.57	0.689
Methods.Timing	4	0.2000	0.0500	0.10	0.981
Residual	18	8.9833	0.4991		
Total	29	11.3417			

l.s.d. F_X: 0.542. T_x: 0.857 F_x*T_x: 1.212 CV(%):8.0

Appendix 20: Analysis of variance for soil total nitrogen before harvesting

Analysis of variance for total Nitrogen, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.111227	0.055613	16.05	
Block.*Units* stratum					
Methods	1	0.007680	0.007680	2.22	0.154
Timing	4	0.007433	0.001858	0.54	0.711
Methods.Timing	4	0.000753	0.000188	0.05	0.994
Residual	18	0.062373	0.003465		
Total	29	0.189467			

l.s.d. F_X: 0.0452. T_x: 0.0714 F_x*T_x: 0.1010 CV(%):9.4

Analysis of variance for total Nitrogen, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.001947	0.000973	0.18	
Block.*Units* stratum					
Methods	1	0.014083	0.014083	2.60	0.124
Timing	4	0.025387	0.006347	1.17	0.355
Methods.Timing	4	0.006000	0.001500	0.28	0.889
Residual	18	0.097320	0.005407		
Total	29	0.144737			

l.s.d. F_X: 0.0564. T_x: 0.0892 F_x*T_x:0.1261 CV(%):9.3

Appendix 21: Analysis of variance for soil available phosphorus before harvesting

Analysis of variance for available Phosphorus, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	26.2968	13.1484	84.21	
Block.*Units* stratum					
Methods	1	0.0780	0.0780	0.50	0.489
Timing	4	0.2518	0.0629	0.40	0.804
Methods.Timing	4	0.0410	0.0102	0.07	0.991
Residual	18	2.8104	0.1561		
Total	29	29.4779			

l.s.d. F_X: 0.3031. T_x: 0.4793: F_x*T_x: 0.6778 CV(%):3.4

Analysis of variance for available Phosphorus, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	3.1766	1.5883	1.90	
Block.*Units* stratum					
Methods	1	1.8253	1.8253	2.19	0.157
Timing	4	1.0589	0.2647	0.32	0.863
Methods.Timing	4	1.0035	0.2509	0.30	0.874
Residual	18	15.0318	0.8351		
Total	29	22.0961			

l.s.d. F_X: 0.701. T_x:1.108 F_x*T_x: 1.568 CV(%):8.1

Appendix 22: Analysis of variance for soil Exchangeable K+ before harvesting

Analysis of variance for soil exchangeable K^+ before harvesting, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.001607	0.000803	0.55	
Block.*Units* stratum					
Methods	1	0.002253	0.002253	1.54	0.231
Timing	4	0.006087	0.001522	1.04	0.415
Methods.Timing	4	0.000247	0.000062	0.04	0.996
Residual	18	0.026393	0.001466		
Total	29	0.036587			

l.s.d. F_X: 0.02938. T_x:0.04645 F_x*T_x: 0.06569 CV(%):9.1

Analysis of variance for soil exchangeable K^+ before harvesting, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.016087	0.008043	1.72	
Block.*Units* stratum					
Methods	1	0.008670	0.008670	1.86	0.190
Timing	4	0.011387	0.002847	0.61	0.661
Methods.Timing	4	0.005013	0.001253	0.27	0.894
Residual	18	0.083980	0.004666		
Total	29	0.125137			

l.s.d. F_X: 0.0524. T_x: 0.0829 F_x*T_x: 0.1172 CV(%):16.8

Appendix 23: Analysis of variance for soil exchangeable Ca^{2+} before harvesting

Analysis of variance for soil exchangeable Ca^{2+} *before harvesting, Kibeho site*

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.1928	0.0964	0.70	
Block.*Units* stratum					
Methods	1	0.2067	0.2067	1.50	0.237
Timing	4	0.6202	0.1550	1.12	0.376
Methods.Timing	4	0.0264	0.0066	0.05	0.995
Residual	18	2.4840	0.1380		
Total	29	3.5301			

l.s.d. F_X: **0.2850**. T_x: **0.4506** F_x*T_x:**0.6372** CV(%):8.8

Analysis of variance for soil exchangeable Ca^{2+} *before harvesting, Kinigi site*

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.03769	0.01884	0.33	
Block.*Units* stratum					
Methods	1	0.21336	0.21336	3.69	0.071
Timing	4	0.25952	0.06488	1.12	0.377
Methods.Timing	4	0.07085	0.01771	0.31	0.870
Residual	18	1.04171	0.05787		
Total	29	1.62314			

l.s.d. F_X: 0.1846. T_x: 0.2918 F_x*T_x: 0.4127 CV(%):7.5

Appendix 24: Analysis of variance for soil exchangeable Mg2+ before harvesting

Analysis of variance for soil exchangeable Mg^{2+} *before harvesting, Kibeho site*

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.03313	0.01656	1.56	
Block.*Units* stratum					
Methods	1	0.01083	0.01083	1.02	0.326
Timing	4	0.01485	0.00371	0.35	0.841
Methods.Timing	4	0.00132	0.00033	0.03	0.998
Residual	18	0.19121	0.01062		
Total	29	0.25134			

l.s.d. F_X: 0.0791. T_x: 0.1250 F_x*T_x: 0.1768 CV(%):5.5

Analysis of variance for soil exchangeable Mg^{2+} *before harvesting, Kinigi site*

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.00049	0.00024	0.00	
Block.*Units* stratum					
Methods	1	0.14145	0.14145	1.74	0.203
Timing	4	0.51941	0.12985	1.60	0.217
Methods.Timing	4	0.06755	0.01689	0.21	0.930
Residual	18	1.45925	0.08107		
Total	29	2.18815			

l.s.d. F_X: 0.2184. T_x: 0.3454 F_x*T_x: 0.4884 CV(%):19

Appendix 25: Analysis of variance for soil CEC before harvesting

Analysis of variance for soil CEC before harvesting, Kibeho site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	93.938	46.969	11.76	
Block.*Units* stratum					
Methods	1	11.894	11.894	2.98	0.102
Timing	4	22.348	5.587	1.40	0.274
Methods.Timing	4	4.554	1.138	0.28	0.884
Residual	18	71.913	3.995		
Total	29	204.647			

l.s.d. F_X: **1.533**. T_x: **2.424** F_x*T_x: **3.429** CV(%):11

Analysis of variance for soil CEC before harvesting, Kinigi site

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.073	0.536	0.25	
Block.*Units* stratum					
Methods	1	5.985	5.985	2.75	0.114
Timing	4	10.430	2.608	1.20	0.345
Methods.Timing	4	2.471	0.618	0.28	0.884
Residual	18	39.107	2.173		
Total	29	59.067			

l.s.d. F_X: . **1.131** T_x:**1.788** F_x*T_x: 2.528 CV(%):9.4