Understanding seed potato selection practices in Uganda

Uta Priegnitz

Propositions

1. Positive selection reduces virus infection when compared to farmers' selection.
   (this thesis)

2. Positive selection fits in the informal seed sector.
   (this thesis)

3. Blanket advice on crop management does not suit smallholder farmers.

4. All farmers are innovative, but they vary in the rate of success.

5. Social interaction has been diluted by our claim culture.

6. Poverty and opulence are administrated in food banks.

Propositions belonging to the PhD thesis, entitled:

Understanding seed potato selection practices in Uganda

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Understanding seed potato selection practices in Uganda

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Abstract

Potato (*Solanum tuberosum* L.) is an important crop for food security and cash income for smallholder farmers in Uganda. However, the national mean potato yield has been in decline to less than 5 Mg ha^{-1} in 2016. Low productivity of potato might be associated with poor and diverse adoption of innovative crop management practices. Smallholder farmers in Uganda commonly use seed potato tubers from the informal sector, especially by seed recycling over several generations. Therefore, seed tubers are highly degenerated with viruses and other diseases, resulting in poor yield and quality of the produce. Over one cycle of multiplication, the degeneration management by positive seed selection was found to be efficient in reducing virus diseases compared with the farmers' method of selection. The aim of this thesis was to provide novel information regarding understanding positive seed selection by investigating it across multiple cycles of multiplication with an interdisciplinary approach. To identify potato farms that are homogeneous in uptake of innovations (use of fertilizer, organic input, fungicides, pesticides, seed selection methods, seed renewal by using quality declared seed, and sole cropping), a farm typology was used and socio-economic characteristics, access to agricultural extension services, memberships of farmers' groups, yield levels of potato and economic return rates were assessed. A farm household survey (n=270) was carried out and principal component analysis and cluster analysis were used to identify types of farms differing in adoption of innovations. Four farm types were identified that demonstrated significant differences in uptake of innovation practices; these differences in uptake were associated with small but significant differences in yield and further in land ownership, availability of labourers and cash, economic return, and access to knowledge. The farm type with relatively high frequencies of using organic input, fungicide input, pesticide input, seed plot technology or positive selection, quality declared seed and sole cropping achieved highest potato productivity; the farm type with relatively frequent use of fungicide input and no use of pesticides was associated with the lowest potato yield. To assess to what extent positive selection over several seasons can reduce incidences of six different viruses in seed lots of different starting quality, multi-seasonal trials were carried out in three locations, with five seed lots from four sources and three cultivars. Detection of viruses was based on DAS-ELISA and Luminex xMAP technology. Results showed fluctuations in some viruses over seasons, with lower Potato leafroll virus (PLRV) and Potato virus X (PVX) incidences in lots from positive selection compared with lots from farmers' selection. Some seed lots were initially highly infected with Potato virus S (PVS) and Potato virus M (PVM) and showed no reduction in virus incidence through positive selection. In general, little infection with Potato virus Y (PVY) and Potato virus A (PVA) was found. To investigate how effectively positive selection enhances yield and underlying crop characteristics, positive selection was compared with farmers' seed selection for up to three seasons in three field trials at different locations. Across all experiments, seasons and seed lots, yields were higher under positive selection than under farmers' selection. The average yield increase resulting from positive selection was 12%, but yield increases were variable, ranging from –5.7% to +36.9%, and in the individual experiments often not significant. These yield increases were associated with higher yields per plant, and mostly higher weights per tuber, whereas the numbers of tubers per plant were not significantly different. Experimentation and yield assessment were hampered by a varying number of plants that could not be harvested because plants had to be rogued from the experimental plots because of bacterial wilt (more frequent under farmers' selection than under positive selection), plants disappeared from the experimental field and sometimes plants did not emerge.To evaluate costs and benefits of positive selection in order to assess its feasibility and affordability, data from the smallholder farms in the four farm types were used for an economic analysis. It showed that farms that already adopted positive selection, invested on average 1.2 extra days (i.e. 2.7 extra labourer days) per acre in positive selection, with an average of 4.0% extra labour costs. A scenario study among the non-adopters of positive selection, assuming a 10% extra yield by carrying out positive selection, showed that a marginal rate of return of adopting positive selection of far above 100% was achieved in every farm type. Gross and net benefit varied because of different yield increases and different selling prices of potatoes in the different farm types, indicating that some farm households benefitted more than others. The present study shows that positive selection does fit in the current seed system for smallholder farmers and has the capacity to increase yield and reduce viruses with visible symptoms compared to farmers' selection. Positive selection being part of the informal and integrated seed sector will help improve seed quality and seed health in farmers' networks.

Keywords: cost-benefit analysis · farm typologies · improved practices · multi-seasonal trials · positive selection · seed degeneration · seed potato economics · *Solanum tuberosum* · Uganda · viruses · yield increase

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CHAPTER 1

General introduction

1.1. Introduction

This thesis studies potato seed selection practices in southwestern Uganda to improve potato yield. The general introduction will treat i) background information on Uganda and its potato production, ii) the informal seed systems in Uganda and their implications, iii) positive selection, iv) study objectives, and v) the structure of the thesis and research methods.

1.2. Background information on Uganda and its potato production

1.2.1. Uganda: Geographical location, population, agro-ecological zones and main crops

Uganda is located in Eastern Africa (Figure 1.1). It is a landlocked country which extends from latitudes 1°29’ S to 4°12’ N and from longitudes 29°34’ E to 35°0’ E. The country borders in the north with South Sudan, in the east with Kenya, in the south with Tanzania and Rwanda, and to the west with the Democratic Republic of Congo. Altitudes are ranging from 620 to 5110 m above sea level (m a.s.l.) (Ugandan Bureau of Statistics, 2017). Population is currently 42,862,958 inhabitants and population growth is among the highest in the world with 3.3% annually, with the majority (83%) living in rural areas (FAO, 2017a). Despite economic growth and a significantly decreased poverty in the last 20 years (The World Bank, 2017), the growing population still remains poor and undernourished in rural areas (FAO, 2017a). In rural areas the agricultural sector is the most important source of income (USAID, 2013). Agriculture accounts for 24% of the country’s GDP, with food crops having the largest share, followed by livestock, forestry, and cash crops.

Agricultural land area (including arable, under permanent crops or under permanent pastures) of the total land area was 71.9% and has increased since 1966 (Knoema, 2016). Arable land (which is defined as land under temporary crops) constitutes about 34.4% of the total land area (Knoema, 2016). Small-scale farming systems are prevailing in Uganda with an average farm size of 0.97 ha (FAO, 2012). Uganda has fourteen agro-ecological zones (Table 1.1) which mainly differ in rainfall, soil type, terrain, crop characteristics, ethnicity and population (Wortmann and Eledu, 1999; Kabeere and Wulff, 2008). Those agro-ecological zones are defining the diverse farming systems throughout the country where different major cash crops like coffee, tea, cotton and tobacco, and important food crops like banana, maize, millet, sorghum, rice, cassava, sweet potatoes, beans and potatoes are produced (Table 1.1, Ugandan Bureau of Statistics, 2017).

Many farmers are not benefitting from the country's economic growth, due to lack of access to agricultural inputs and infrastructure, and no access to markets (Fuglie and Marder, 2015). Therefore, crop productivity needs to be improved and further investment in agriculture is crucial in order to achieve sustainable, long-term food security, growth of the GDP, and rural economic development (Conceição et al., 2016).

1.2.2. Potato in Uganda

Potatoes are produced worldwide and potato is the 3rd largest food crop after rice and wheat (Birch et al., 2012; Haverkort and Struik, 2015). The consumption of potato is growing fast in the developing world and has an important role in enhancing food security (Navarre and Pavek, 2014). The potato crop has advantages over cereals like: it yields more food and calories per land unit (Navarre and Pavek, 2014), has a short cropping cycle, and it is

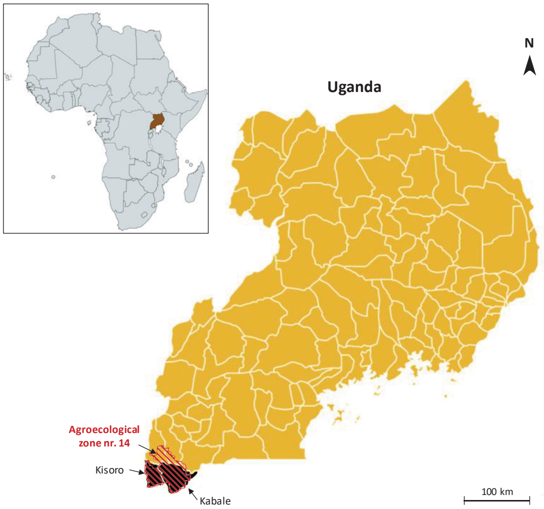

Figure 1.1. Map of Uganda indicating the study regions for this thesis: Kabale and Kisoro district in the agroecological zone number 14

Table 1.1. Uganda agro-ecological zones, main crops grown and their characteristics (adapted from Wortmann and Eledu, 1999 and Kabeere and Wulff, 2008)

Agro-ecological zones	Main crops grown	Mean annual precipitation (mm)	Mean annual temperature (°C)	Land that is farmland (%)
1 West Nile Farmlands	Tobacco, cotton, Arabica coffee, sesame, finger millet, sorghum, cassava, groundnut	1304	23	68
2 North-western Farmlands-Wooded Savanna	Tobacco, cotton, Arabica coffee, sesame, finger millet, sorghum, cassava, groundnut, sunflower	1174	25	29
3 Northern Moist Farmland	Cotton, tobacco, sesame, finger millet, sorghum, cassava, sunflower, groundnut, sweet potato, been, maize	1258	24	69
4 Northeast-central Grass-Bush - Farmlands	Cotton, tobacco, sesame, finger millet, sorghum, cassava, sunflower, groundnut, sweet potato	1134	24	41
5 North-eastern Semi-arid Short Grass lands	Finger millet, cassava, sorghum, bean, maize, cotton, groundnut, sesame, sweet potato, Irish potato sunflower, arabica coffee, banana, wheat, rice	795	23	11
6 Western Mid Altitude Farmlands and Semliki Flats	Robusta coffee, Arabica coffee, banana, maize, bean, sweet potato, Irish potato, cassava, horticultural crops, tea, groundnut, cotton, wheat, millet, rice, sorghum	1123	22	47
7 Central Wooded Savanna	Cotton, Robusta coffee, Arabica coffee, bean, maize, banana, cotton, wheat, millet, rice, Irish potato, sweet potato	1170	23	5
8 Southern and eastern Lake Kyoga Basin	Cotton, Robusta coffee, bean, maize, banana, sweet potato, cassava, horticultural crops, tea, groundnut	220	23	64
9 Mt. Elgon Farmlands	Banana, cassava, potato, Arabica coffee, Robusta coffee, wheat, barley, cotton, maize, bean, millet, rice	1337	20	68
10 Western Medium High Farmlands	Banana, cassava, potato, Arabica coffee, wheat, barley, cotton, maize, bean, millet, rice, sorghum	1140	20	68
11 Southwestern Grass Farmlands	Arabica coffee, Robusta coffee, banana, cotton, maize, bean, wheat, millet, rice, Irish potato, sweet potato, cassava, sorghum, horticultural crops, tea, groundnut	851	21	30
12 Lake Victoria Crescent and Mbale Farmlands	Banana, coffee, Robusta coffee, maize, sweet potato, root crops, cotton Finger millet, cassava, sorghum, bean, horticultural crops, tea, groundnut	1211	22	64
13 Ssese Islands and Sango Plains	Finger millet, cassava, sorghum, bean, maize	1400	21	5
14 Southwestern Highlands	Banana, cassava, potato, Arabica coffee, wheat, barley, cotton, maize, bean, millet, rice	1177	16	77

more efficient in water use (Birch et al., 2012). Moreover, potatoes have a rich nutritional value in containing important vitamins, minerals, well digestible proteins and carbohydrates (Navarre and Pavek, 2014).

The potato (*Solanum tuberosum* L.) is an important food and cash crop for smallholder farmers in Sub-Saharan Africa, and Uganda is one of the largest potato producing countries in East Africa (Okoboi et al., 2014; FAO, 2017b).

The potato crop was probably introduced around 1900 by British colonial administrators (International Potato Center (CIP), 2006). Another source of introduction came most likely from border countries like Kenya, Rwanda and Congo. Most production zones around 1945 were in the Kigezi highlands in southwestern Uganda and the Bugisu highlands in eastern Uganda. At the end of the 1940's production was severely affected by late blight (causal agent *Phytophthora infestans)* and to a minor extent by early blight (causal agent *Alternaria solani*) (International Potato Center (CIP), 2006). Due to increasing demand and imports of the potato crop the Department of Agriculture formed in 1966 the Kigezi Potato Development Scheme. In Makerere University a breeding programme was established in 1968. Since the early 1970's the National Agricultural Research Organisation (NARO) released over 15 potato varieties (Kaguongo et al., 2008; Okoboi et al., 2014). At present, the Kigezi highlands in the agro-ecological zone no. 14 (Figure 1.1) are providing most of the national potato production, with an output of 135,210 Mg on 26,096 ha (Bonabana-Wabbi et al., 2013; Ugandan Bureau of Statistics, 2017).

Most farmers in the Kigezi highlands are growing potatoes twice a year: in the long (mid-August to mid-December) and in the short (February to mid-May) rainy seasons. Sometimes also a third season (after the short rainy season) is used (Gildemacher et al., 2009b). Potato yield in Uganda is less than 5 Mg ha^{-1} (FAO, 2017b), which is low in comparison to production statistics for many other countries and considering that a potential yield of 25 Mg ha^{-1} can be achieved (International Potato Center, 2011; Okoboi et al., 2014).

1.2.3. Reasons for limited potato productivity

There are several causes for low potato yields in Uganda. According to Fuglie (2007), high ranking diseases are viruses, especially Potato leaf roll virus (PLRV), Potato virus Y (PVY), and Potato virus X (PVX). Virus diseases in the seed tuber are widespread in Uganda and have a major negative impact on seed tuber health (Salazar, 1996; Kinyua et al., 2012). Reasons for high virus pressure in the environment can be a high vector occurrence; aphids are the main vectors of virus transmission. Of other major importance are diseases like bacterial wilt caused by *Ralstonia solanacearum* and late blight induced by *Phytophthora infestans;* they cause severe yield and quality losses for potato farmers in Sub-Saharan Africa. A study by Kigundu et al. (2019) showed that bacterial wilt infection becomes rampant in Kabale district, which causes severe yield losses. Drought and poor agronomic practices, such as inadequate soil fertility management, disease control management and post-harvest management also hamper potato yields of smallholder farmers (Scott et al., 2013, Gildemacher et al., 2009b).

However, poor seed quality is the major yield-constraining factor in Sub-Saharan Africa including Uganda (Machangi et al., 2003; Gildemacher et al., 2009a). Poor seed quality is a result of seed degeneration. Potato is vegetatively propagated and in successive cycles pests and pathogens are accumulating in the planting material. If a potato plant becomes infected with e.g. a virus, tubers may become infected, carry the virus, and if planted produce infected progeny plants and tubers, which leads to low yields and a degeneration of the seed potato stock. This may result in reductions up to 90% compared to healthy plants (Guzmán-Barney et al., 2012). Poor seed quality is thus a result of a less developed and a poorly functioning seed system.

1.3. The informal seed systems and its implications

The final yield and tuber quality in potato production depend on the quality of the planted seed tubers (Struik and Wiersema, 1999). In agriculture, seed is the overall basis in crop production and seed quality determines production and yield (Louwaars and de Boef, 2012; McGuire and Sperling, 2013). Uganda lacks a well-developed formal seed system; most seed in Uganda is sourced

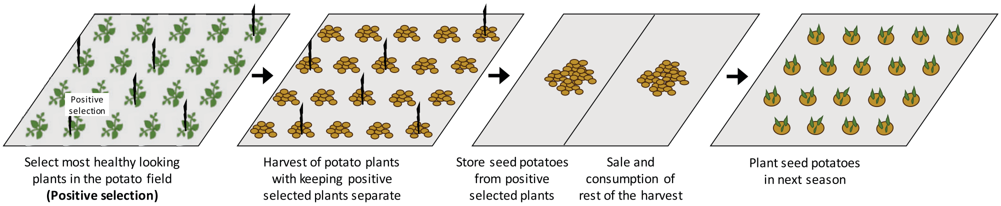

Figure 1.2. Scheme of positive selection in a common potato field

informally, with seed quality not ensured (Gildemacher et al., 2009a; Okoboi et al., 2014). The majority of potato producers in Uganda keep tubers to be used as seed from their own harvest of the ware potato crop (recycling). Without proper management, farm-saved seed tubers are often highly degenerated due to accumulation of seed-borne pests and diseases such as viruses and other pathogens (Gildemacher et al., 2009b; Gildemacher et al., 2011; Thomas-Sharma et al., 2016). Larger tubers are generally sold as ware potatoes while smaller-sized tubers, which often contain viruses, are kept for seed. A study in Kenya showed that informally sourced seed potatoes from the rural market were 99.6% infected with major virus diseases (Gildemacher et al., 2009a).

The common method or “Farmers’ Practice” to select seed potatoes for the next season is to choose small or medium-sized tubers from the bulk of the harvest to be used as seed without considering the health status of these tubers. Sources for purchasing seed besides the own harvest are from informal sources like the village market or neighbours.

To prevent a decrease in seed quality by planting the infected tuber, renewing the seed stock with healthy tubers from a reliable source is crucial for progeny health (Struik and Wiersema, 1999). In Uganda, only few potato farmers derive quality-declared seed from the formal sector like specialized seed growers (Gildemacher et al., 2009a). According to a survey by Gildemacher (2009a), only 26% of the potato farmers in Uganda renew their seed, and if they do, the average renewal interval is seven seasons. In addition, purchasing quality seed potatoes is expensive for smallholder farmers (Kaguongo et al., 2008) which makes regular replenishment of seed potatoes very difficult due to lack of cash; also, some farmers are not willing to pay for quality seed.

To improve seed potato quality and thereby increase yield for smallholder farmers the methods positive seed selection and seed plot technique were developed and investigated over one growing cycle (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012).

1.4. Positive selection

In carrying out positive selection (PS) (Figure 1.2), healthy looking plants in ware potato crops are pegged before flowering to potentially serve as seed for the next season (Gildemacher et al., 2007). At harvest, tubers from pegged plants are separately collected from those of non-pegged plants, checked for tuber health and judged for tuber size to serve as seed for the next generation. In this way, the (most) healthy tubers from the farmer's field are planted in the next season and can produce healthy plants and tubers and increase yield (Schulte-Geldermann et al., 2012). In carrying out the seed plot technique (SPT), a separate plot of tubers is grown by the farmer for production of seed tubers. Within this plot, positive selection is applied (by pegging again the healthy plants for seed) and tubers from the pegged plants are used to establish the next-season seed plot, whereas the remaining tubers are used to grow the ware crop. Potatoes are planted at a high density in a disease-free small plot to achieve an optimum rate of multiplication of tubers per area (Kakuhenzire et al., 2005; Kinyua et al., 2012). In addition, better control measures of pests and diseases can be carried out in the seed plot.

Positive seed selection was found to be effective in gaining more yield and reducing virus incidence but was only investigated during one growth cycle (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012). On-farm trials also showed lower levels of wilted plants in crops grown from positive selected seed (Schulte-Geldermann et al. 2012). Positive selection achieved an average yield increase of 28% (yield increase varied between -4% to 58%, Gildemacher et al., 2011) and 30% (yield increase varied between 23-35%, Schulte-Geldermann et al., 2012) compared to common farmers' practice in one season. Positive selected plants compared to farmers' practice of selection reduced the infection rate of PLRV with 12.1%, PVX with 2.6%, and PVY with 13.4% (Schulte-Geldermann et al., 2012). In Gildemacher et al. (2011) the visual virus incidence was reduced from 9% in farmers' selected seed plots to 5% in positive selected seed plots, and from 18.8% in farmers' selected seed plots to 7.1% in positive selected seed plots in one cropping cycle. It appears that viruses that were not tested in those studies, as Potato virus S, Potato virus M, and Potato virus A play an important role in Uganda, like described for the neighbouring country Kenya (Muthomi et al., 2009; Were et al., 2013). The visual bacterial wilt infection in plants was reduced from an average of 3.5% in farmers selected seed plots to 1.3% in positive selected seed plots, respective from 7.6% in farmers selected seed plots to 2.6% in positive selected seed plots (Gildemacher et al., 2011).

The mechanisms behind positive selection and virus incidence are not fully understood; this is partly due to the fact that positive selection was, at the onset of my research, only studied for one season in on-farm trials, only for a limited number of different viruses (PVY, PVX, PLRV) and only by measuring yield as fresh tuber yield in Mg ha^{-1} (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012).

With the described benefits of yield increases and a reduced infection rate mentioned, extension personnel in Eastern Africa promoted positive seed selection as a solution and innovation for smallholder farmers who cannot invest cash in renewing seed potatoes or for covering their seed potato expenses. However, the uptake and adoption of positive selection on smallholder farms in southwestern Uganda remains unknown. Gildemacher et al. (2012) estimated the additional labour costs for farmers in applying positive selection based on estimated costs. Hence, only little information is available for calculating the real costs a farmer spends on positive selection.

1.4.1. Towards understanding positive selection

For understanding positive selection and its full potential or even a possible regeneration, it is necessary to carry out field experiments over several generations, in multiple locations, with different seed potato sources, investigating multiple virus incidences, monitoring of vectors for possible virus transmission, and breaking down the final yield into different yield components. It was expected that by using high-quality starting material, healthier plants and hence higher yields in the first planting season of consecutive multiplication cycles would be achieved. However, the degeneration rate of those potato stocks under farmer's practice remain largely unknown (as how fast will the degeneration in later stages of consecutive field multiplications be). Investigations were essential for understanding and quantifying the effects on virus incidence and yield components of the improved seed selection technique and to look for its suitability and uptake by smallholder farmers.

For addressing the missing information of what percentage of farmers and what group of farmers with common characteristics have already adopted positive selection, a sociological study was needed to investigate innovation awareness and uptake of seed technologies (positive selection, seed plot technique) among smallholder farmers. For calculating the real costs a farmer spends on positive selection, all main production and labour costs need to be taken into account in order to get a 'full picture' of gross and net benefit for farmers. To date, no studies have been reported considering positive selection in a detailed cost-benefit analysis integrating all other main agricultural management practices and to ensure and evaluate the affordability and feasibility of implementation.

1.5. Study objectives

The overall objective of this thesis was to improve the availability and production of healthy seed potatoes for smallholder farmers in southwestern Uganda by reducing degeneration caused by viruses, by stimulating the regeneration of own produced seed, and by evaluating the adoption and applicability of positive selection in seed production and to compare positive selection with the current practice of farmer's seed selection from the tuber harvest.

To achieve the overall objective, specific objectives of the research were discerned as followed:

i) To analyse agronomic, social, and socio-economic characteristics of the potato producing farm types in southwestern Uganda differing in the adoption of innovative production practices, including positive selection (Chapter 2);

ii) To quantify effects of positive selection across multiple generations on incidence of different viruses in the seed potato tubers (Chapter 3) and how this affected tuber yield and yield components (Chapter 4);

iii) To evaluate costs and benefits of positive selection in order to assess its feasibility and affordability for different types of small-scale farmers (Chapter 5).

1.6. Structure of the thesis and research methods

The main goal of the thesis is to assess and study positive seed selection using a multidisciplinary approach.

Chapter 1 is a general introduction to potato production in Uganda with insights into the constraints of the informal potato seed system and a possible solution to overcome the shortage of seed supply and their costs.

Chapter 2 describes results of semi-structured interviews with potato farmers in Kabale and Kisoro district in southwestern Uganda to gain better insight into current choices of innovative agricultural practices. The analysis employed descriptive statistics and a multivariate approach to group farms according to the uptake of innovations and to deepen the understanding which farm households actually have taken up, among others, positive selection. Innovation uptake was detected to understand variation in potato yield, by identifying agronomic, social, and socio-economic characteristics.

To obtain data for quantifying positive selection, field experiments were carried out at three locations during four subsequent seasons with in total five different starting seed lots. Positive selection was compared to the common method, farmers' selection. **Chapter 3** focuses on different virus incidences (PLRV, PVX, PVY, PVA, PVS and PVM) in potato seed tubers. To quantify effects of selection methods on changes in the fraction of virus-infected tubers the virus detection methods LUMINEX and DAS-ELISA were employed.

Effects of positive selection on tuber yield were assessed in **Chapter 4** evaluating potato yield and yield components, like yield per plant, weight per tuber, number of tubers per plant, from the field experiments described in Chapter 3.

Chapter 5 builds on Chapters 2 and 4 and assesses the economic potential in adopting positive selection in the different farm types. A cost-benefit analysis is carried out to assess the economic feasibility of positive selection for potato farmers in the different farm types identified in Chapter 2. The general discussion in **Chapter 6** presents and discusses the main findings of this thesis. Recommendations for adoption are developed, future perspectives are addressed and implications for seed improvement are discussed.

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CHAPTER 2

A farm typology for adoption of innovations in potato production in southwestern Uganda

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Abstract

In Uganda, low productivity of potato might be associated with poor and diverse adoption of innovative crop management practices. This paper aims to identify the potato farm typologies in southwestern Uganda, i.e. collections of farms that are homogeneous in uptake of innovations (use of fertilizer, organic input, fungicides, pesticides, seed selection methods, seed refreshment by using quality declared seed, and sole cropping), and to analyse these typologies based on socio-economic characteristics, access to agricultural extension services, memberships of farmers' groups, yield levels of potato and return rates. A farm household survey (n=270) was carried out and principal component analysis and cluster analysis were used to identify types of farms differing in adoption of innovations. Four farm types were identified that demonstrated significant differences in uptake of innovation practices; despite the small differences in yield among farm types, differences in uptake were associated with significant differences in the yield and further in land ownership, availability of labourers and cash, economical return, and access to knowledge. The farm type with relatively high frequencies of using organic input, fungicide input, pesticide input, seed plot technology or positive selection, quality declared seed and sole cropping achieved highest potato productivity; the farm type with relatively frequent use of fungicide input and no use of pesticides was associated with the lowest potato yield. The findings emphasise associations between innovation uptake and farm characteristics. Opportunities for improvement through extension services and shared knowledge can achieve wider adoption, enhance potato productivity and increase income for smallholder farmers.

Keywords extension services · improved practices · multivariate analysis · socio-economic factors   *Solanum tuberosum* · yield increase

2.1. Introduction

The agricultural sector in Uganda plays a vital role in food security, poverty reduction, economic development, and income generation (Diao et al., 2010; Salami et al., 2010; Benin et al., 2012; Proctor, 2014). Uganda is dominated by small-scale farms with an average size of 0.97 ha (FAO, 2012). In the agro-ecological zone *montane system* in southwestern Uganda, potato (*Solanum tuberosum* L.) is important for food security and cash income for the smallholder farmers (Wortmann and Eledu, 1999; Gildemacher et al., 2009b; Okoboi et al., 2014). Introduced already in the early 20th century by colonial administrators (International Potato Center, 2006), the potato has multiple agronomic advantages above other traditional food crops, including a short cropping cycle, high production per unit area and per unit of water, and a highly nutritious produce (Woldegioris et al., 2013; Haverkort and Struik, 2015). Potato often serves as a hunger breaking crop during food shortages, especially in Eastern Africa (Gildemacher, 2012; Haverkort and Struik, 2015).

The districts Kabale and Kisoro, located in the Kigezi highlands (1,500-3,000 m a.s.l.) in southwestern Uganda where potato is traditionally grown, are the most important production areas of potato (Kaguongo et al., 2008; Bonabana-Wabbi et al., 2013). Kabale produced more than 45,578 Mg of potato tubers and Kisoro more than 25,617 Mg of potato tubers in the year 2008/09 (census from July 2008 until September 2009; Ugandan Bureau of Statistics, 2017). Together, this comprised more than 46% of the total national potato production in Uganda (Ugandan Bureau of Statistics, 2017). The local environmental conditions of the mountainous districts are favourable for potato cultivation, with mild temperatures, abundant rainfall and deep volcanic soils (Ferris et al., 2002). However, the national mean potato yield was approximately 7 Mg ha^{-1} in the years 1999 - 2007 (Food and Agriculture Organization of the United Nations, 2018) and since 2008 it has been in decline to less than 5 Mg ha^{-1} in 2016 (Food and Agriculture Organization of the United Nations, 2018). This yield is low in comparison to the production statistics of many other countries and considering that a yield of 25 Mg ha^{-1} is attainable (International Potato Center, 2011). In the neighbouring country Rwanda, with similar agro-ecological conditions, the average yield is found to be 14.2 Mg ha^{-1} (Knoema, 2016).

In Uganda several major constraints are causing these low yields for smallholder farmers: lack of adoption of proper soil fertility management, lack of adoption of pesticides and fungicides to combat pests and diseases, lack of use of clean and improved seed tubers, and lack of sole potato cropping (Manrique, 1993; Struik and Wiersema, 1999; Gildemacher et al., 2009a; Gildemacher et al., 2009b; International Potato Center, 2011; Schulte-Geldermann et al., 2013; Wang'ombe and van Dijk, 2013; Thomas-Sharma et al., 2016). A study from 2005 by Gildemacher (2012) showed that only 4.7% of the farmers used chemical fertilizer, and only 17.7% used farmyard manure. Okoboi et al. (2014) found in their study from 2008/09 that in the Kigezi region 18.1% of the farmers used fertilizers, 29.2% of the farmers used fungicides, and 0.5% of the farmers used quality seed. Supply of seed to farmers by private and semi-public sector institutions is rare in East-African countries (Tadesse et al., 2016). Moreover, sole potato cropping can lead to significantly higher yields and an increase in tuber yield per plant compared to intercropping (Manrique, 1993). These yield constraints can be summarised as inadequate agricultural practices related to poor adoption of innovative management practices to enhance the yield of the potato crop. Innovations are defined here as "an idea, practice, or object that is perceived as new by an individual or other unit of adoption" (Rogers and Everett, 1983).

To produce quality seed potatoes for improving potato yield, two innovative applications of low-cost technologies have been promoted by extension officers, namely positive selection (PS) and the seed plot technology (SPT)[1] (Kakuhenzire et al., 2005; Gildemacher et al., 2007). The common way in Uganda of choosing seed tubers for the next season consists of selecting tubers from the bulk of the harvest from the ware potato crop. Furthermore, farmers can buy quality declared seed tubers from the seed grower association

[1] In carrying out positive selection, healthy-looking plants in ware potato crops are pegged just before flowering, to potentially serve as sources of seed for the next season. In this way, the healthiest tubers from the farmer's field are planted in the next season and can produce healthy plants and tubers with increased yield. In the seed plot technology, a separate plot of tubers is grown by the farmer for production of seed tubers. Within this plot, positive selection is applied and tubers from the pegged plants are used to establish the next-season seed plot, whereas the remaining tubers are used to grow the ware crop. Both methods may improve the availability of healthy seed tubers to the farmers.

UNSPPA (Ugandan National Seed Potato Production Association) or from KAZARDI (Kachwekano Zonal Agriculture Research and Development Institute).

Although programmes and initiatives from the agricultural extension service promote the use of innovations (Okoboi et al., 2014), little research has been undertaken to assess their uptake. Variation in adoption of innovative management practices which enhance potato yield and economical crop return, is associated with differences in socio-economic characteristics of the farm households and in their access to agricultural extension services (Bidogeza et al. 2009; Tadesse et al. 2017). All farm resources (e.g. land, labour, cash for investment) are the foundation of a farmer's wealth and the economic capacity of his farming system (Tittonell et al., 2010) and are classified in socio-economic characteristics and potato farming attributes. Agricultural extension services, either public or private, as well as farmer groups, act as advisors, providing valuable knowledge and information with regards to the use and adoption of innovative management practices (Ortiz et al., 2013). Rogers (1983) also demonstrated that farmers having contacts outside their local community were more open to adopting new management techniques.

To increase potato production for improved food and cash security it is critical to understand the complexity of smallholder farms in Uganda and to understand the use of appropriate technological innovations (Giller et al., 2011; Tittonell et al., 2010). To get insights in the diverse and specific farm types it is necessary to evaluate the uptake of innovations in the potato production system in combination with the socio-economic characteristics (cf. Kuivanen et al., 2016), the access to extension services and the variation in yield among potato farmers. Farmers in southwestern Uganda are faced with limitations like shortage of land for crop production (Salami et al., 2010; Whitney et al., 2018); potato was specifically promoted for land scarce farm households (Aliguma et al., 2007). Additionally, land degradation due to soil nutrient depletion contributes to a decrease in agriculture production in Uganda (Pender et al., 2004; Nkonya et al., 2008; Kirui and Mirzabaev, 2014).

Therefore, the development of farm typologies is a first but pivotal step to analyse the adoption of innovative farm management practices in smallholder farms. Such typologies could help to support more robust policy interventions and advisory programmes to enhance the adoption of techniques to increase potato yields (Banerjee et al., 2014). They can also be used to help develop more suitable agricultural policies for less-favoured regions (Ruben and Pender, 2004).

This study explores the uptake of innovative management practices of smallholder potato production in southwestern Uganda and the packages of practices in which farmers have adopted them. Adoption of innovative agricultural management is defined here in terms of the following improved practices: (i) use of chemical fertilizer, (ii) use of organic inputs, (iii) use of fungicides, (iv) use of pesticides, (v) use of either SPT and/or PS, (vi) use of KAZARDI and/or UNSPPA seed, and (vii) use of sole cropping of potato. These improved practices were used to form clusters of farms based on how innovations were taken up by farmers. For these clusters, differences in their socio-economic characteristics, additional potato farming practices and access to extension services were assessed. The final result is the identification of potato farm typologies with different potato productivity and returns for the southwestern Ugandan region.

The main objective of this research is to define farm typologies based on the uptake of innovative farm management practices in potato cultivation. Specific objectives of this paper are (i) to assess the variation in the uptake of innovative farm management for potato cultivation; (ii) to identify relevant packages of innovations (clusters) taken up by various farm types using Principal Component Analysis (PCA) and Cluster Analysis (CA), and (iii) to generate farm types with different production systems thereby exploring how yields, economical return, socio-economic characteristics and access to extension services differ among the typologies.

Based on this analysis, the adoption of specific agronomic management practices in different farm types can be better understood. This can then be used to help implement policies, which could better support potato farmers in the Kabale and Kisoro districts of Uganda. Our analysis identifies farm-specific constraints and opportunities for agricultural development and interventions.

2.2. Materials and methods

This study assessed and characterised the adoption of innovative farm management practices and explored associated potato yields and farm types in southwestern Uganda in three steps. First, general potato production and management characteristics were assessed through literature review, field observations, and discussions with key informants, including farmers and personnel from the Kachwekano Zonal Agriculture Research and Development Institute (KAZARDI), Uganda. The second step included the use of a semi-structured questionnaire to collect detailed information from smallholder potato farmers in the region. In the third step, the collected data were analysed using PCA and CA to identify homogeneous groups differing in uptake of innovations and in farm type.

2.2.1. Study area and survey

A semi-structured questionnaire was used in the districts Kabale and Kisoro (southwestern highlands of Uganda) to collect data on potato production practices by smallholder potato farmers. These districts were selected because they represent the major potato cropping areas in Uganda (Kaguongo et al., 2008; Bonabana-Wabbi et al., 2013; Ugandan Bureau of Statistics, 2017) (Figure 2.1). The districts are located close to the borders of Rwanda and the Democratic Republic of Congo, and about 340 km west of the capital Kampala (distance Kampala to Kabale town). Kabale and Kisoro are located at altitudes ranging from 1,500- 3,000 m a.s.l. (Bonabana-Wabbi et al., 2013) and belong to the agro-ecological zone *montane system* (Kabeere and Wulff, 2008). The annual rainfall in the *montane system* zone varies between 1,000 and 1,500 mm, mainly distributed over two rainy seasons, from March to May and from September to November (Low, 2000; Ferris et al., 2002).

The semi-structured questionnaire was pre-tested in December 2013 and April 2014 with 15 farmers in Kabale and Kisoro districts. The questionnaire was then refined and revised with closed and open-end questions to enhance further discussion. In total, 270 farmers were interviewed face-to-face in the local language by specifically trained enumerators in June 2014, 141 farmers in Kabale district and 129 farmers in Kisoro district (Table A2.1).

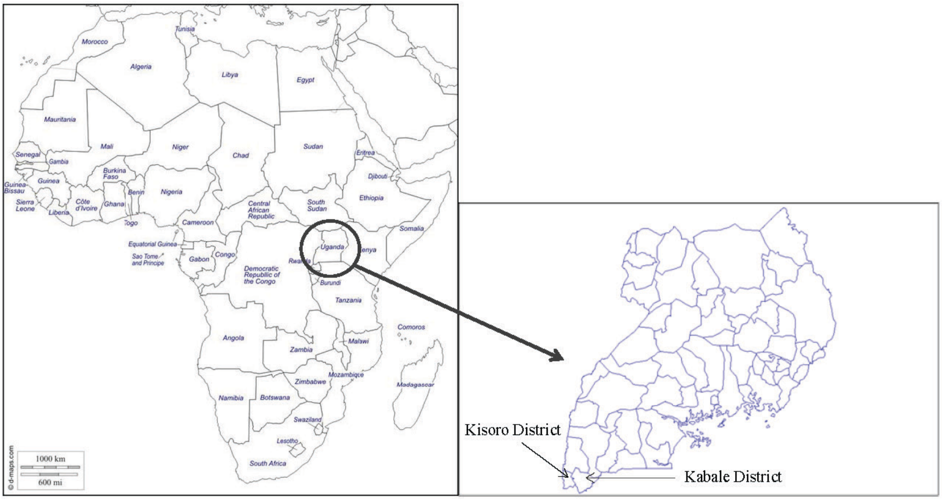


Figure 2.1. Geographic location of the study site

A district represents the administrative division by the local government and is further divided into counties, sub-counties, parishes and finally into villages. Four sub-counties per district (Table A2.1) were randomly selected from the 19 sub-counties in Kabale district and the 14 sub-counties in Kisoro district. Per sub-county, the National Agricultural Advisory Service (NAADS) agents mobilised potato farmers to gather at a meeting point; from there, farmers were randomly selected for the interviews. Farmers from sixteen parishes in the four sub-counties of the Kabale district and from eleven parishes in the four sub-counties in the Kisoro district were present (Table S2.1). From the 270 interviews, 11 surveys were excluded in the analysis because the respondents were not the household head or spouse. Therefore 259 interviews were retained in the analysis.

The information collected (Table 2.1) included characteristics of the farm household head or spouse (name, gender, age, education, household size, and occupation), of the farm (total crop area, crop diversity), information on hired and family farm labour, access to advisory service and farmer groups, and on the potato crop on the farm (area for potato production, production season, potato management practices (including adoption of innovations, potato varieties grown, seed source), occurrence of pests and diseases in the potato crop, yield, market price, and awareness of the existence of seed selection techniques). Cropping area was recorded in acres (1 ha is equal to 2.47 acres) and derived from the farmers' estimation by using equivalent known areas, i.e. a soccer pitch. All costs were reported and calculated in Ugandan Shillings (UGX) and finally converted to US Dollar (exchange rate 30th June 2014: 1 USD = 2600 UGX).

Our research was carried out with informed oral consent by all participants. Confidentiality of all information from all respondents was secured. Research protocols guaranteed that it was impossible to link published, aggregated data to individuals. We followed the applicable guidelines and regulations for ethics that are common for surveys as reported in this paper. Based on consultation with the applicable ethical committee of Wageningen University and specialists in Uganda, we were assured that under such conditions, special permission from the Wageningen University ethical committee was not required.

2.2.2. Data analysis

Data analysis was done using SPSS (Statistical Package for Social Science), version 23.0. A multivariate approach was used to construct farm typologies. First, a principal component analysis (PCA) was used to reduce the number of variables into a new set of components. Seven variables regarding uptake of innovative farm management practices were chosen for the PCA (use of fertilizer, use of organic input, use of fungicide, use of pesticide, use of SPT and/or PS, use of quality declared seed (in the last five seasons) and use of sole cropping of potato (vs. intercropping it). Four principal components exceeding, according to Kaiser's criterion, an eigenvalue of 1.00 were retained (Table 2.2). The Kaiser-Meyer-Olkin (KMO) measure for sampling adequacy indicated a relatively low value of 0.4; however, Bartlett's test of sphericity with an associated p-value of <0.001 indicated that the analysis would be valid. Evaluating the correlations between the factors and the four components, a loading of greater than 0.50 was considered for deciding of how many components to be used. With the identified components, a hierarchical, agglomerative cluster analysis (CA) was carried out using Ward's method to

Table 2.1. Description of the variables, units, number of respondents, and minimum and maximum values of the variables used in the principal component analysis and cluster creation (variables in bold), and the subsequent characterization of farm types.

Name of variable	Description and units	n	Minimum	Maximum
Uptake of innovations in potato farming				
Use of fertilizer	**= 1 if fertilizer input, 0 if no fertilizer input**	**259**	**0**	**1**
Use of organic input	**= 1 if organic input, 0 if no organic input**	**259**	**0**	**1**
Use of fungicide	**= 1 if fungicide input, 0 if no fungicide input**	**259**	**0**	**1**
Use of pesticide	**= 1 if pesticide input, 0 if no pesticide input**	**259**	**0**	**1**
Use of SPT or PS[1]	**= 1 if using either/and SPT or PS, 0 if none is applied**	**259**	**0**	**1**
Use of quality declared seed[2]	**= 1 if quality declared seed was used in the last 5 seasons, 0 if no quality declared seed was used**	**259**	**0**	**1**
Use of sole cropping	**= 1 if sole cropping, 0 if mixed cropping**	**259**	**0**	**1**
Number of innovations	= number of innovations taken up	259	0	7
Return of potato farming				
Yield in Mg ha^{-1}	= potato yield in Mg per ha	258	2.0	37.1
Price per bag	= selling price per bag of 100 kg in Ugandan Shilling	255	40,000	150,000
Total return per year per farm in UGX	= total return per year of potato per farm in Ugandan Shilling	255	100,000	36,550,000
Access to extension service and knowledge				
Advisory service	= 1 if access to advisory service, 0 if no access	259	0	1
NAADS[3]	= 1 if access to NAADS service, 0 if no access	259	0	1
Farm group	= 1 if member of a farm group, 0 if no member	259	0	1
Years of farming potato	= number of years of potato growing on farm	259	1	49
Socio-economic characteristics				
Characteristics of the farm household				
District	= 1 if Kabale, 0 if Kisoro	259	0	1
Household head gender	= 1 if male, 0 if female	259	0	1
Household size total	= number of household members	259	1	15
Respondent's age	= respondent's age in years	259	19	74
Respondent's education	= 1 if higher than primary school, 0 if no education or primary education	259	0	1
Own mobile[4]	= 1 if respondent is in possession of own mobile phone, 0 if not in possession of mobile phone	259	0	1
Other business than farming[4]	= 1 if respondent is engaged in other business, 0 if only farming	258	0	1
Acres ownership	= acres of land in possession	257	0.1	15
Total acres farmland	= acres of land farmed in total	257	0.1	16
Crop diversity	= number of other crops grown besides potato	259	1	6
Labour in potato farming				
Hired labour average	= average number of hired people per acre and farm activity	253	0	25.0
Family labour average	= average number of family members per acre and farm activity	253	0	11.0
Average days of labour	= average number of days per farm activity	253	1	18.5
Marketing	= 1 if direct marketing, 0 if not	259	0	1

[1] SPT refers to seed plot technology, PS refers to positive selection
[2] Quality declared seed refers here to UNSPPA seed and/or KAZARDI seed
[3] National Agriculture Advisory Service
[4] Reported for respondent

<u>*Potato farming attributes*</u>				
Areas and seasons				
Acres potato per year	= total acres of potato during the year	255	0.13	10
Seasons with potato	= number of seasons per year in which potato is grown	259	1	3
Potato in long season	= 1 if potato is grown in long season (October- January), 0 if not	259	0	1
Potato in short season	= 1 if potato is grown in short season (February-June), 0 if not	259	0	1
Potato in off-season	= 1 if potato is grown in off-season (May- September), 0 if not	259	0	1
Inputs				
Use of NPK fertilizer[5]	= 1 if only NPK fertilizer use, 0 if no NPK use	259	0	1
Quantity of fertilizer[6]	= quantity of fertilizer in kg per acre for farmers using fertilizer	142	1	750
Quantity of pesticide[6]	= quantity of pesticide in l per acre for farmers using pesticide	178	0.01	8
Quantity of fungicide[6]	= quantity of fungicide in kg per acre for farmers using fungicide	185	0.25	75
Use of chemical storage input	= 1 if chemical storage input is used, 0 if not	259	0	1
Seed-related characteristics				
Knows about SPT and/or PS	= 1 if respondent has knowledge about existence of SPT and/or PS, 0 if not	259	0	1
Last two seasons quality declared seed	= 1 if in last two seasons quality declared seed was used, 0 if not	259	0	1
Bulk of harvest seed	= 1 if seed is used from bulk of harvest, 0 if not	259	0	1
Market seed	= 1 if seed is used from local market, 0 if not	259	0	1
Neighbour seed	= 1 is seed is used from neighbour/fellow farmer, 0 if not	259	0	1
Cv. Rwangume	= 1 if cv. Rwangume is used, 0 if not	259	0	1
Cv. Kinigi	= 1 if cv. Kinigi is used, 0 if not	259	0	1
Cv. Rwashaki	= 1 if cv. Rwashaki is used, 0 if not	259	0	1
Cv. Victoria	= 1 if cv. Victoria is used, 0 if not	259	0	1
Cv. Katchpot 1	= 1 if cv. Katchpot 1 is used, 0 if not	259	0	1
<u>*Incidence of diseases and pests*</u>				
Bacterial wilt	= 1 if bacterial wilt disease in potato, 0 if not	259	0	1
Late blight	= 1 if late blight disease in potato, 0 if not	259	0	1
Virus	= 1 if virus disease in potato, 0 if not	259	0	1
Aphids	= 1 if aphids in potato, 0 if not	259	0	1
Leaf miners	= 1 if leaf miners in potato, 0 if not	259	0	1
<u>*Reasons for not expanding potato cropping*</u>				
Cash limit seed	= 1 if cash limit for buying seed is a factor, 0 if not	259	0	1
Land limitation	= 1 if land limitation is a factor, 0 if not	259	0	1
Pests and diseases	= 1 if pests and diseases are a factor, 0 if not	259	0	1
High input costs	= 1 if high input costs are a factor, 0 if not	259	0	1

Bold section refers to the variables used in the PCA and clustering

[5] Across the farmers who stated they are using it

[6] When quantity was provided by respondent

minimise the variance within a cluster and squared Euclidean distance for measuring the distances. The agglomeration process leading to clusters of farms that differed in the uptake of innovations is presented in the dendrogram (Figure 2.2).

After clustering based on the uptake of innovations, one-way ANOVA was used to test for significant differences between clusters for all variables in the categories 'uptake of innovations', 'socio-economic characteristics', 'potato farming attributes', 'access to extension service and knowledge' and 'returns of potato farming'. The variables from the first four categories that differed significantly between clusters were used to characterise the farm type of a cluster, the variables from the last class were used to describe the returns of that farm type. Fisher's LSD test was used for mean separation between the clusters. Finally, based on the analysis distinguished characteristics were used for determining the wealth of the farm type.

Table 2.2. Factor loadings from the four components resulting from the Principal Component Analysis with eigenvalues and percentages variance explained

Innovation practice	Component			
	1	2	3	4
Use of fertilizer	0.074	**-0.747**	0.056	0.418
Use of organic input	0.002	**0.829**	0.055	0.312
Use of pesticide	0.019	0.028	0.022	**0.915**
Use of fungicide	**0.830**	0.033	-0.290	0.088
Use of either SPT and/or PS	0.083	0.025	**0.922**	0.022
Use of quality declared seed	**0.577**	-0.025	0.393	-0.029
Use of sole cropping	**0.649**	-0.048	0.204	-0.008
Eigenvalue	1.59	1.23	1.10	1.03
Variance accounted for (%)	22.8	17.6	15.7	14.7
Cumulative variance accounted for (%)	22.8	40.4	56.1	70.9

Bold numbers indicate factor loadings higher than 0.5 or lower than -0.5

SPT = seed plot technology; *PS* = positive selection

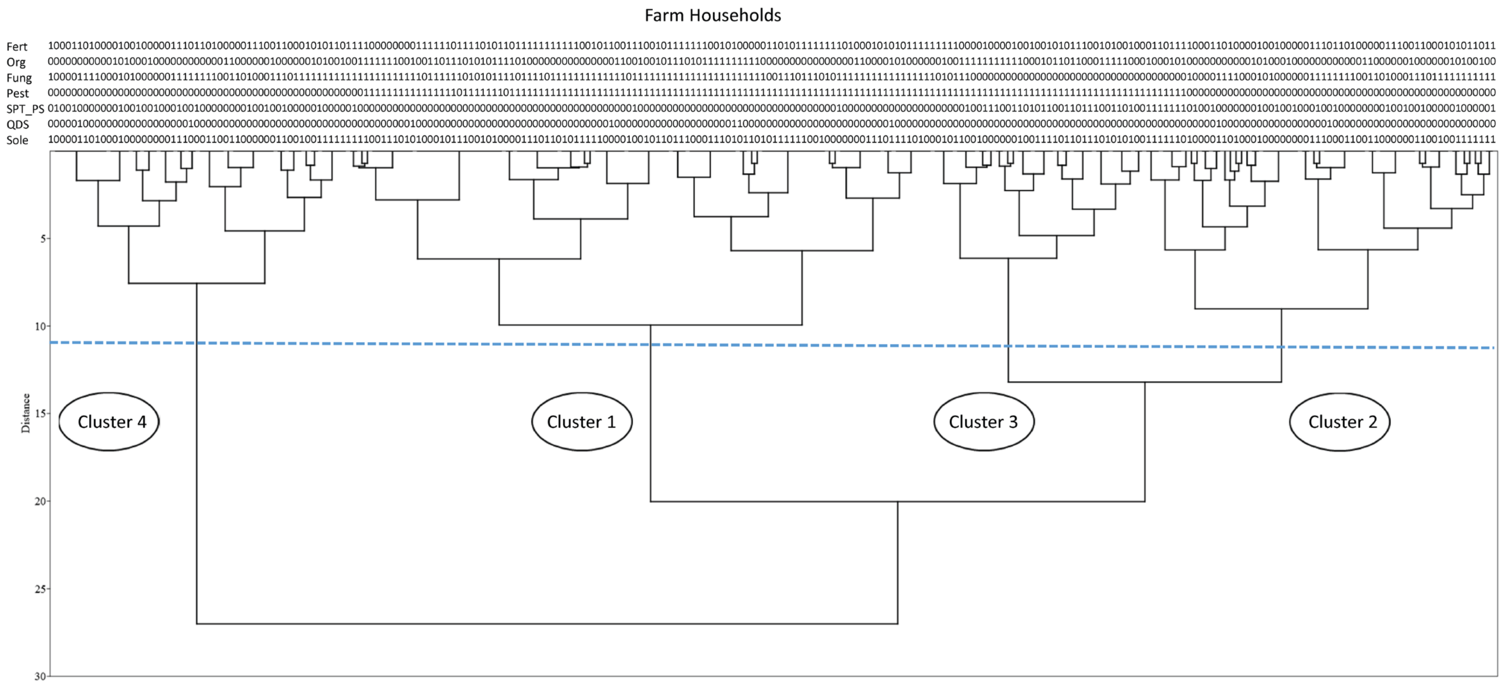


Figure 2.2. Dendrogram for the Cluster Analysis. On top are the codes ‘1’ for ‘use’ or ‘0’ for ‘non-use’ of innovations (Fert= Fertilizer input, Org= Organic input, Fung= Fungicide input, Pest= Pesticide input, SPT_PS= use of SPT and/or PS, QDS= use of quality declared seed, Sole= use of sole crop) which lead to the clustering. The dashed line represents the agglomeration coefficient (the distance between the clusters) and the selected cut-off point for forming the four cluster solutions.

2.3. Results

2.3.1. General characteristics

2.3.1.1. Socio-economic characteristics

Characteristics of the farm and farm households
Of the respondent's households, 88% were male headed (Table 2.3); the average respondent age was 42.6 years and 25% of the respondents had an education higher than primary school. Total household size was on average 6.7 people. Farmers had on average 2.66 acres of farmland, of which they owned on average 2.30 acres. Only 23% of the respondents were engaged in businesses other than farming. Other crops grown on the farm beside potato were maize, beans, sorghum, sweet potato and other crops (data not shown).

Labour in potato farming
Per management practice (1st land ploughing, 2nd land ploughing, planting, weeding, spraying, harvesting), on average 6.3 labourers per acre were hired. Family labour input was on average 1.9 people per acre. The average number of days per management practice was 2.3 days.

2.3.1.2. Potato farming attributes

Areas and seasons
The potato farming attributes (Table 2.3) show that potato was grown in three seasons; 84% of the farmers grew potato in the long season (October-January), 91% in the short rainy season (February-June), and 47% in the off-season (May-September). Per year, per farm an average of 1.88 acres of land were dedicated to potato farming.

Seed-related characteristics
Most farmers planted seed tubers that were selected from the bulk of their own harvest (65%), and/or bought on the market (58%); seed was also obtained from neighbours and/or fellow farmers (29%) (Table 2.3, potato farming attributes). In the last two seasons, 11% had been using quality declared seed (Table 2.3, potato farming attributes). Of all farmers, 68% stated they

knew about SPT and/or PS (Table 2.3, potato farming attributes). The most frequently grown cultivars were Kinigi (grown by 60% of the farmers), Rwangume (grown by 57%), Rwashaki (25%), and Victoria (grown by 24%) (Table 2.3, potato farming attributes).

Incidence of diseases and pests, reasons for not expanding potato cropping
Major diseases reported were bacterial wilt (77%) and late blight (50%). Aphids (57%) were reported as the major pest (Table 2.3, potato farming attributes). The main reasons for not expanding potato cropping was land scarcity (67%) or not enough cash to buy seed potatoes (64%) (Table 2.3, potato farming attributes).

2.3.2. Uptake of innovations in potato farming

Regarding uptake of innovations (Table 2.3), 55% of the farmers used fertilizer on potato, 41% used organic inputs, 72% used fungicides, and 73% used pesticides. Fertilizer was applied with an average amount of 101.2 kg/acre (Table 2.3, potato farming attributes). Farmers who used fertilizer were mostly using NPK fertilizer (42% of the farmers). Pesticide was applied with an average of 1.4 litre/acre, and fungicide with 5.2 kg/acre. Quality declared seed, like seed from UNSPPA or KAZARDI, was used in the last five seasons only by 15% of the farmers (Table 2.3, uptake of innovations). Of the farmers, 68% knew about PS and/or SPT (Table 2.3, potato farming attributes), whereas 37% of all farmers stated they actually used it (Table 2.3, uptake of innovations). Potato was sole cropped by 58% of the farmers. The rest of them used potato in a mixed cropping system, mainly mixing potato with beans and/or maize. On average, farmers had taken up 3.5 innovations out of the 7, in different packages (Table 2.3).

2.3.3. Return of potato farming

In relation to return of potato farming (Table 2.3), farm households achieved an average yield of 9.5 t/ha, with a selling price per 100 kg bag of around 29 USD (69,913 UGX). Yield and selling price were variable: reported yield varied between 2.0 and 37.1 Mg ha^{-1} (8-150 bags of 100 kg per acre) and selling price varied between 40,000 and 150,000 UGX per bag (equates to 15.38 USD to 57.70 USD per bag of 100 kg).

2.3.4. Access to extension services and knowledge

Of the farm households, 68% had access to any of the agricultural extension services (NAADS, Africa 2000 Network, International Fertilizer Development Center or A2N) (Table 2.3) and 56% of all farm households had access to NAADS; 71% stated they were member of a farm group. The farm household had between 1 and 49 years of experience with growing potato, with an average of 13 years (Table 2.3).

2.3.5. Principal component analysis results and clustering of farms based on uptake of innovative potato practices

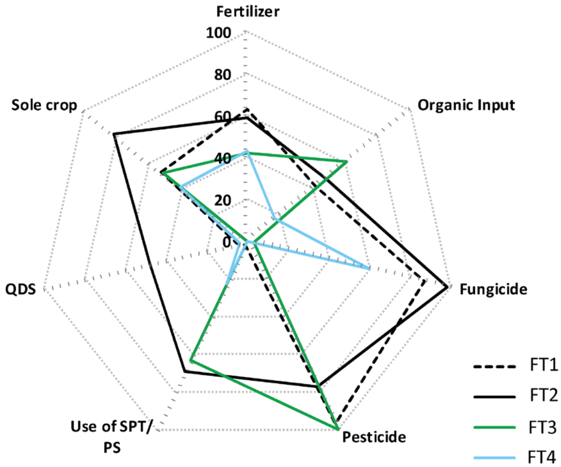
The PCA on the seven variables regarding uptake of innovations resulted in the extraction of four principal components, accounting together for 70.9% of the total variance (Table 2.2). The first component accounted for the greatest share of the variance with 22.8%. This correlated positively with use of fungicide, use of quality declared seed potatoes, and with sole cropping of potato suggesting the uptake of these practices was related. The second component explained 17.6% of the variance; it correlated positively with organic input use and negatively with chemical fertilizer application, suggesting the uptake of these practices was, to some extent mutually exclusive. The third component accounted for 15.7% of the variance; it correlated positively with adoption of PS and/or SPT. This suggests that the uptake of these particular practices could be used to identify farms that fall into a cluster. Finally, the fourth component explained 14.7% of the variance; it correlated with the adoption of use of pesticides, again suggesting the possibility of identifying farms in a cluster through use of pesticides alone.

The clustering procedure resulted in the agglomeration schedule and the four-cluster-cut-off points in the dendrogram (Figure 2.2). Based on studying innovation use the uptake or no uptake is shown in the dendrogram with code '1' for uptake, and code '0' for no uptake. In the dendrogram (Figure 2.2), it is shown that Cluster 4 separates from all other clusters largely based on the non-use of pesticides, while in the other clusters (especially 1 and 3) they are used widely. This is in line with PC4 showing significant correlations with the use of pesticides (Table 2.2). After Cluster 4, Cluster 1 separates from Cluster 2 and 3, largely based on the almost non-use of SPT and/or PS, which is related to PC3 in Table 2.2. Finally, Cluster 2 separates from Cluster 3, likely based on the use of the factors showing correlations with PC1 (use of sole cropping, use of quality declared seed, and use of fungicides). The innovations correlating to PC2 (use of fertilizer and organic input) will explain differences between the higher order of branches seen within the dendrogram within a cluster. The farm households thus were grouped into four clusters for which the farm types were assessed. These four typologies were grouped based on the uptake of innovations. Then they were characterised for the different characteristics with respect to use of innovations, socio-economic features, access to extension services and returns of potato farming.

2.3.6. Farm type characterisation from clusters

Table 2.3 shows the resulting four different clusters described as farm types (FT) with their characteristics. For naming the farm types, distinctive characteristics of the innovation uptake were used that are based on number of innovation (Table 2.3, Figure 2.3). The characterization of the innovations taken up in the different farm types was based on the significant differences, where values not differing significantly from the lowest value were eliminated as characterizing a specific farm type (Figure 2.3).

Cluster 1: Innovative farms was the largest cluster with 40.1% (n = 104) of the farms. Of the farmers in this group, 63% used fertilizer, 97% used pesticides, and 87% used fungicides. Only 2% used PS and/or SPT, and only 5% used quality declared seed. Of all farmers in this group, 53% stated that they planted potato as sole crop. The average number of innovations taken up was 3.5; fertilizer and/or organic input, fungicide and pesticide were used frequently. Average yield was the second highest among the four FTs with 10.3 Mg ha^{-1}. Regarding the selling price of one potato bag, farmers in this FT ranked also second; they earned 71,759 UGX (around 27.60 USD) per 100 kg bag. They possessed the second highest access to advisory service (72%),



	Fertilizer	Organic Input	Fungicide	Pesticide	Use of SPT/ PS	QDS	Sole crop
FT 1	x	x	x	x			
FT 2	x		x	x	x	x	x
FT 3		x		x	x		
FT 4			x		x		

Figure 2.3. Percentages of farm households in each Farm Type (FT) which are using the individual innovations; the table underneath represents the package of innovation use for each Farm Type (FT)

NAADS (57%) and average membership to a farm group (72%). Land size owned was second largest with 2.27 acres on average.

Cluster 2: Highly innovative farms represented 24.3% (n = 63) of the farms. Regarding input use, they scored second on adoption of fertilizer use (59%) and organic input use (48%) and had the highest adoption of fungicide use (98%). They had high adoption of PS and/or SPT with 69% and the highest adoption of quality declared seed with 48% of the farm households. In this cluster, potato was largely grown as a sole crop. The average number of innovations taken up was 4.8 and highest of all farm types; the frequent use of organic input, fungicide, pesticide, SPT/PS, quality declared seed and sole cropping were prevailing. This farm type received the highest amount of money per potato bag sold (73,371 UGX= 28.22 USD per 100 kg bag) and had the highest yield with 10.8 Mg ha^{-1} although both were not significantly higher than in Cluster 1. The relative uptake of distinctive innovation practices like organic input, fungicide use, pesticide use, use of SPT/PS, quality declared seed and sole cropping is in line with the highest yield. This group presented the highest use of hired labour, with 7.8 people on average per acre, per season and per farm practice. Main characteristics were the largest proportions of having access to advisory service (93%) or NAADS (78%) and involvement in a farm group (92%). This group possessed the most land (2.89 acres on average), farmed also the largest area with potato per year (2.27 acres) and included the largest percentage farmers growing potato in the off-season (62%). Only 68% of the farmers in this group stated they had bacterial wilt in the crop, which was the lowest incidence of the four farm types.

Cluster 3: Semi-innovative farms accounted for 14.7% (n = 38) of the farms and can be described also as medium innovative farms (but differed from Cluster 1 in the using seed selection and not using fungicides). Referring to organic inputs, farmers in this typology had the highest adoption percentage with 61%, but the lowest adoption of fertilizer use with 42%. They were all using pesticides, but only 3% used fungicides. Over the last five seasons, they had not used any quality declared seed. However, 63% used PS and/or SPT. The average number of innovations taken up was 3.2, with frequent use of organic input and pesticide and use of SPT/PS. The yield was the second lowest with 8.3 Mg ha^{-1}. The selling price of potato was also the second lowest with an average price of 66,891 UGX (around 25.73 USD) per bag of 100 kg. Their access to advisory service (57%), NAADS (50%) and farm group membership (78%) was the second lowest of all clusters. They possessed the least amount of land with 1.73 acres on average. Additionally, 89% stated they had bacterial wilt in the crop, which was the highest incidence and significantly different to farms in Cluster 2.

Cluster 4: Low innovative farms comprised 20.5% (n = 53) of the farm households. Farmers' adoption of fertilizer use (43%) was second lowest among the four FTs; besides, the percentage farms using organic input was lowest with only 17%. The farms did not use any pesticides, but 60% used fungicides. Regarding seed quality, 23% used PS and/or SPT and 4% used quality declared seed. Intercropping potato was done by 59% of the farmers. The average number of innovations taken up was 1.8 and the lowest of all

Table 2.3. Characteristics of the farm households and the four identified farm typologies including the p-value of one-way analysis of variance of differences between farm types

Category and characteristic[1]	Mean (n= 259)	Cluster 1 (FT1) (n=104) Innovative farms	Cluster 2 (FT2) (n=64) Highly innovative farms	Cluster 3 (FT3) (n=38) Semi-innovative farms	Cluster 4 (FT4) (n=53) Low innovative farms	p-value
Uptake of innovations in potato farming						
Use of fertilizer	**0.55**	**0.63 b**	**0.59 ab**	**0.42 a**	**0.43 a**	**0.030**
Use of organic input	**0.41**	**0.42 b**	**0.48 bc**	**0.61 c**	**0.17 a**	**0.000**
Use of fungicide	**0.72**	**0.87 c**	**0.98 d**	**0.03 a**	**0.60 b**	**0.000**
Use of pesticide	**0.73**	**0.97 c**	**0.77 b**	**1.00 c**	**0.00 a**	**0.000**
Use of SPT or PS	**0.37**	**0.02 a**	**0.69 c**	**0.63 c**	**0.23 b**	**0.000**
Use of quality declared seed	**0.15**	**0.05 a**	**0.48 b**	**0.00 a**	**0.04 a**	**0.000**
Use of sole cropping	**0.58**	**0.53 a**	**0.82 b**	**0.52 a**	**0.41 a**	**0.000**
Number of innovations	3.5	3.5 b	4.8 c	3.2 b	1.8 a	0.000
Return of potato farming						
Yield in Mg ha^{-1}	9.49	10.3 bc	10.8 c	8.3 ab	7.2 a	0.001
Price per bag	69,913	71,759 bc	73,371 c	66,891 ab	64,019 a	0.001
Total return per year per farm in UGX	5,212,803	5,954,350 bc	6,858,032 c	4,600,263 ab	2,763,676 a	0.001
Access to extension service and knowledge						
Advisory service	0.68	0.72 b	0.93 c	0.57 ab	0.41 a	0.000
NAADS	0.56	0.57 b	0.78 c	0.50 ab	0.34 a	0.000
Farm Group	0.71	0.72 b	0.92 c	0.78 bc	0.50 a	0.000
Years of farming potato	13.23	14.8	13.1	12.0	12.3	0.224
Socio-economic characteristics						
Characteristics of the farm household						
District	0.53	0.66 c	0.53 bc	0.34 ab	0.20 a	0.000
Household head gender	0.88	0.93	0.93	0.86	0.88	0.490
Household size total	6.4	6.7	6.6	6.5	5.7	0.118
Respondent's age	42.6	42.4	44.7	41.4	41.0	0.380
Respondent's education	0.25	0.21	0.34	0.18	0.28	0.180
Own mobile	0.74	0.73 b	0.85 b	0.81 b	0.58 a	0.005
Other business than farming	0.23	0.25	0.21	0.13	0.23	0.454
Acres in ownership[2]	2.30	2.27 ab	2.89 b	1.73 a	1.83 a	0.015
Total acres of farmland[2]	2.66	2.66	3.24	2.31	2.21	0.068
Crop diversity	2.80	2.8	2.8	2.8	2.6	0.558

Labour in potato farming						
Hired labour average	6.34	6.4 ab	7.8 b	6.1 ab	4.9 a	0.004
Family labour average	1.98	1.9	2.1	1.9	1.8	0.691
Average days of labour	2.33	2.6	1.8	2.2	2.2	0.059
Marketing	0.15	0.09	0.21	0.18	0.16	0.167
Potato farming attributes						
Areas and seasons						
Acres potato per year[2]	1.88	1.97 b	2.27 b	1.96 ab	1.36 a	0.015
Seasons with potato	2.22	2.18 a	2.46 b	2.21 ab	2.15 a	0.036
Potato in long season	0.84	0.79	0.90	0.86	0.86	0.263
Potato in short season	0.91	0.92	0.93	0.89	0.90	0.865
Potato in off-season	0.47	0.46 ab	0.62 b	0.44 ab	0.37 a	0.047
Inputs						
Use of NPK fertilizer	0.43	0.50 b	0.54 b	0.34 ab	0.22 a	0.001
Quantity of fertilizer[2]	101	77.1 b	67.4 b	25.0 a	20.4 a	0.000
Quantity of pesticide[2]	1.39	1.25 c	0.87 b	1.35 c	0.01 a	0.000
Quantity of fungicide[2]	5.26	5.13 c	4.50 bc	0.18 a	2.44 ab	0.003
Use of chemical storage input	0.25	0.25	0.35	0.23	0.17	0.154
Seed-related characteristics						
Knows about SPT and/or PS	0.68	0.64	0.75	0.67	0.67	0.565
Last two seasons quality declared seed	0.11	0.04 a	0.34 b	0.00 a	0.03 a	0.000
Bulk of harvest seed	0.65	0.68	0.59	0.60	0.71	0.438
Market seed	0.58	0.50	0.54	0.63	0.71	0.058
Neighbour seed	0.29	0.26	0.32	0.31	0.26	0.812
Cv. Rwangume	0.57	0.54	0.50	0.65	0.85	0.460
Cv. Kinigi	0.60	0.67	0.57	0.55	0.62	0.488
Cv. Rwashaki	0.25	0.25	0.29	0.23	0.24	0.897
Cv. Victoria	0.24	0.20	0.31	0.18	0.24	0.345
Cv. Katchpot1	0.05	0.00 a	0.10 b	0.07 ab	0.09 b	0.011
Incidence of diseases and pests						
Bacterial wilt	0.77	0.74 ab	0.68 a	0.89 b	0.84 b	0.041
Late blight	0.50	0.51	0.53	0.44	0.50	0.864
Virus	0.27	0.28	0.29	0.28	0.20	0.686
Aphids	0.57	0.66	0.54	0.50	0.52	0.185
Leaf miners	0.24	0.29	0.28	0.21	0.11	0.063

Reasons for not expanding potato cropping						
Cash limit seed	0.64	0.63	0.65	0.68	0.73	0.639
Land limitation	0.67	0.64	0.65	0.73	0.75	0.444
Pests and diseases	0.45	0.53 c	0.35 ab	0.52 bc	0.24 a	0.002
High input costs	0.41	0.47	0.32	0.39	0.37	0.306

Bold section refers to the variables used in the PCA and clustering

Means with different *letter*s in a row indicate significant difference ($p < 0.05$) according to Fisher's LSD test

[1] For full explanation of the characteristics, see Table 2.2

[2] The number of respondents underlying the mean was different from n=259; for exact numbers see Table 2.2

farm type groups, with frequent use of fungicides and SPT/PS. In this farm type, yield was lowest (7.2 Mg ha^{-1}). Besides, their return for one bag of potato was also lowest with an average price of 64,019 UGX (around 24.62 USD per 100 kg bag). Respondents from the farms in this group had the lowest possession of own mobile phone devices (58%). Moreover, this group had the lowest access to advisory service (41%) and lowest membership of a farm group (50%). This group grew the smallest acreage of potato per year (1.92 acres), whereas ownership of land was on average 1.83 acres. Hired labour was lowest in this group with on average 4.9 people per acre, per farm practice and per potato season.

2.4. Discussion

The objectives of this paper were to define the uptake of innovations in potato production in different farm households in southwestern Uganda, by assessing the variations and relevant packages of improved practices (typologies), and how the farm types in these clusters differ in socio-economic characteristics, access to extension services, yield and economical return. The dissimilarities in characterisation of the typologies exposed one farm type with higher innovation uptake (FT 2: highly innovative farms), two farm types with medium innovation uptake (FT 1: innovative farms and FT 3: semi-innovative farms) and one farm types with low innovation uptake (FT 4: low innovative farms).

2.4.1. Uptake of agricultural innovations

Farmers are using different packages of innovations: no innovation package was commonly used by all FTs (Figure 2.3). Summarizing, the relative frequent use of organic input, fungicide input, pesticide input, SPT and/or PS, quality declared seed and sole cropping (FT 2) led to a higher potato yield than the relative frequent use of fungicide input and PT and/or PS (FT 4), which resulted in the lowest potato yield. FT 1 showed low innovation in seed input (little use of SPT and/or PS, and little use of quality declared seed) and also less used sole cropping compared to FT 2. No farm household in FT 4 used pesticides, which might be explained by low financial resources. In general, organic input, fungicide input, pesticide input and use of SPT and/ or PS were adopted in three out of four FTs in different packages and can be seen as relevant for farmers (Figure 2.3, Table 2.3). The uptake of fertilizer might be related to the financial resources available to the farm households. It can be assumed that innovations like fertilizer input, quality declared seed, and sole crop are too expensive or do not fit in the current production systems of the farmers. We further like to mention trade-offs in using agro-chemicals in an inappropriate way which can harm humans and the natural environment; some farmers might choose the traditional way of not using any agro-chemicals. Interventions to increase potato production is never a 'one size fits all' approach, it is more a 'basket of options' (Ronner, 2018) where farmers can and are able to choose what works best for them to increase sustainable crop production.

Interestingly, all groups showed similar awareness of PS and/or SPT (Table 2.3), but the lowest adoption was found in FT 1. PS and/or SPT are generally practices advised for resource-poor farmers to adopt, due to their lack of financial capital to buy quality seed. However, these were also found to have a very high adoption rate in the highly innovative farms (FT 2). This might also show that FT 2 is more aware of the importance of planting good quality seed tubers.

A larger percentage of the highly innovative farmers (FT 2) used quality declared seed than of the low innovative farmers (FT 4) and medium innovative farmers (FT 1 and 3), where adoption was only 0 – 5%. This finding is in line with the idea that only wealthier farmers could afford the quality declared seed (Gildemacher et al., 2011). Sole cropping of potato was done most by FT 2, which might be related to the possession of more land and following the recommendations of extension personnel.

2.4.2. Socio- economic characteristics determining wealth of farm types

FT 1 and FT 2 were classified as wealthier farm types than FT 3 and FT 4 because of significantly more capacity to hire labour, higher yield and selling price characteristics; more farmers in those two groups belonged to Kisoro district. Land ownership was more dominant in FT 2 than in FT3 and FT

4; more acres of land were owned, and more potato was grown throughout the year in FT 1 and 2 than in other FTs. This is reflected also in labour availability: more labourers were hired on FT 2 farms than on FT 4 farms, likely because those farm households could afford to hire labour. FT 4 had the lowest possession of mobile phones; mobile phones play a crucial role in coordination and communication among all stakeholders, access to necessary information and production inputs (Ortiz et al., 2013).

Unexpected results regarding characteristics of the farm households were the findings that gender and education level of the household head were not different among farm types (Table 2.3). Total acres of farmland and crop diversity were also not important in characterizing the different farm types. There were also no differences in experience in growing potato among farm types. Most farmers in all FTs grew potato in the long-rainy and short-rainy season, but more farmers in FT 2 than in FT 4 grew potato in the off-season, with intermediate values for the other FTs; growing more potato throughout the year might gain more profit. The FTs also showed the same incidence in using informal seed sources (seed from own bulk of harvest, market and neighbours). Quality declared seed was significantly more used in FT 2, which is in line with more wealth or purchasing power. There was no difference in prevalence of most potato cultivars between the FTs; an exception was found for Katchpot 1 that was found especially in FT 2 and FT 4, but this cultivar was not grown frequently. Farm types did not differ in incidence of pests and diseases, except for bacterial wilt, which was lower in FT 2 than in FT 3 and 4. Every farm type also had largely the same reasons for not expanding potato cultivation: cash limitation for buying seed, land limitation and high input costs; only pests and diseases were more frequently mentioned in FT 1 and FT 3 than in FT 4. Many features of the farm households were actually very similar among farm types.

2.4.3. Access to extension services and knowledge

Access to extension services plays an increasingly important role in innovation with respect to adoption, productivity and income (Ortiz et al., 2013). This is in line with FT 4 having the lowest access to extension services and having the lowest adoption rate of innovative practices, and the lowest productivity and income from potato. Okoboi et al. (2014) specified that continuous information from extension services leads to higher uptake of innovation. Therefore, resource-poor farmers should be enabled and empowered to seek assistance and support from multi-stakeholder initiatives to take up other agricultural practices for yield productivity and bargaining power.

2.4.4. Yield and economical return of potato farming

While FT 2 is the most innovative farm type (high innovation adoption, high hired labour input and highest access to extension services), the output regarding potato yield and the selling price of potato were also the highest. Comparing this with FT 4 as low innovative group (low innovation adoption, lowest hired labour input, lowest access to extension services), the yield of potato for this FT4 was the lowest and this also applied for the selling price of a potato bag (Table 2.3). More adoption of innovative farm management practices leads to higher yield. It can be argued that especially the frequent adoption of planting good quality seed (either quality declared seed or using SPT or PS) led to an improved potato yield in FT 2. A lower selling price for low innovation farmers may be explained by poorer quality of the potato tubers, or by growing potato mainly when supply is high (i.e. not the off-season, Table 2.3). Other contributing factors are probably a lower bargaining power of these farmers, which can further be explained by low access to extension services, such as farmer cooperatives (cf. Bonabana-Wabbi et al., 2013). Poorer quality of the produce is also demonstrated by the fact that in FT 3 and FT 4 the highest incidence of bacterial wilt in the potato crop occurred; this can be regarded as a weakness.

2.5. Conclusions

Our approach to use multivariate statistical methods proved to be practical and functional in identifying farm types with characteristics that hinder or enhance the adoption of innovations. The main findings in our study are (i) farm households differ from high (FT 2) to low (FT 4) adoption of innovation practices and innovation packages, with intermediate adoption rates in FT

1 and FT 3; (ii) farm households with highest innovation adoption (FT 2) have a) more access to extension services and knowledge, and b) possess more land, labour and cash; and (iii) farm households with strong adoption in innovation practices (FT 1 and FT 2) generate a higher potato yield and more income. The innovation package characterised by using organic input, fungicide input, pesticide input, SPT and/or PS, quality declared seed and sole cropping was related with the highest potato yield and more income, compared to the package using only relatively frequently fungicide input and SPT/PS which was associated with the lowest potato yield and lowest income. Exploring why some farmers have a lower adoption rate than other farmers, we acknowledge that farmers' choose according to their managerial abilities what is most relevant and possible; also actual benefit and risk perception play important roles in the rate of uptake of innovations (Wigboldus et al., 2016). Nevertheless, poor farm types require improvement and support in many areas, like access to extension services and shared knowledge, bargaining power, productivity and innovation, to become empowered to enhance productivity in a sustainable way.

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Supplementary material

Table A2.1. Number of potato producing farm households surveyed per potato cropping district, sub-county and parish

District	Sub-county	Parish	Number
Kabale	Hamurwa	Hamurwa	18
		Igomanda	1
		Kakore	3
		Mpungu	3
		Ruhonwa	5
		Shebeya	4
	Ikumba	Mushanje	1
		Nyamabare	23
		Nyaruhanga	11
	Kamuganguzi	Buranga	7
		Kasheregenyi	7
		Katenga	11
		Kicumbi	3
		Kisaasa	6
		not specified	1
	Muko	Butare	25
		Karengyere	12
Kisoro	Bukimbiri	Iremera	10
		Kagunga	22
	Kanaba	Kagezi	16
		Muhindura	14
	Muramba	Bunagana	4
		Gisozi	12
		Muramba	5
		Sooko	11
	Nyarusiza	Gasovu	2
		Rukongi	32
		not specified	1
Total			**270**

CHAPTER 3

Impact of positive selection on incidence of different viruses during multiple generations of potato seed tubers in Uganda

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Abstract

Smallholder farmers in Uganda commonly use seed potato tubers from the informal sector, especially by seed recycling over several generations. Therefore, seed tubers are highly degenerated with viruses and other diseases, resulting in poor yield and quality of the produce. Over one cycle of multiplication, degeneration management by positive seed selection was found to be efficient in reducing virus diseases compared with the farmers' method of selection. The objective of this study was to assess to what extent positive selection over several seasons can reduce six different virus incidences in seed lots of different starting quality in southwestern Uganda. Multi-seasonal trials were carried out in three locations, with five seed lots from four sources and three cultivars. Detection of viruses was based on DAS-ELISA and Luminex xMAP technology. Analysis was carried out with Analysis of Variance (ANOVA) on angular transformed percentages of virus incidence. Results showed fluctuations in some viruses over seasons with lower *Potato leafroll virus* (PLRV) and *Potato virus X* (PVX) incidences in lots from positive selection compared with lots from farmer's selection. In contrast, some seed lots were initially highly infected with *Potato virus S* (PVS) and *Potato virus M* (PVM) and showed no reduction in virus incidence through positive selection. In general, little infection with *Potato virus Y* (PVY) and *Potato virus A* (PVA) was found. Based on these results it is recommended that smallholder farmers are trained in positive selection to opt for less virus infected plants and tubers thus increasing potato production.

Keywords Multi-seasonal trials · Positive selection · Seed degeneration · Seed potatoes · Seed regeneration · Uganda · Viruses

3.1. Introduction

In Uganda, potato is an important food and cash crop for farmers. However, low productivity of the crop associated with poor quality of harvested tubers is a major concern. Potatoes are vegetatively propagated by means of tubers, called seed tubers, from the harvest of a seed potato crop or selected from the harvest of a ware potato stock. Final yield and tuber quality of ware potatoes depend on the quality of the planted seed tubers (Struik and Wiersema, 1999). Poor seed tuber quality is a major production constraint, especially in Eastern Africa, including Uganda (Gildemacher et al., 2009; Thomas-Sharma et al., 2016). Farmers in Uganda have poor or no access to high-quality seed and commonly use their own recycled seed potatoes, or seed tubers from the informal sector, including the local market, family or neighbours (Gildemacher et al., 2009; International Potato Center 2011). Farmers generally select seed tubers from the bulk of the potato harvest based on seed size and visual inspection; this method is further referred to as farmers' selection.

Degeneration of seed potatoes can be defined as a decline in seed potato quality by a build-up of pathogens and pests over subsequent generations, and is primarily caused by viruses (Loebenstein and Gaba, 2012; Thomas-Sharma et al., 2016). It occurs when seed tubers are recycled for several subsequent field generations under conditions that are conducive to (re-) infection. Incidence of potato viruses in potato seed tubers can be high and these viruses can significantly reduce seed tuber health status (Salazar, 1996; Kinyua et al., 2012). Substantial yield reductions with *Potato leaf roll virus* (PLRV) of up to 90% have been reported (Jeffries, 1998; Guzmán-Barney et al., 2012). According to Fuglie (2007), especially PLRV, *Potato virus Y* (PVY), and *Potato virus X* (PVX) cause severe yield and quality losses for potato farmers in Sub-Saharan Africa.

In general, two ways of virus infection are taking place: primary virus infection and secondary virus infection. Primary virus infection occurs when a healthy potato plant becomes infected with a virus. The virus multiplies in the plant and virus particles systemically translocate to the tubers. Secondary infection occurs when infected daughter tubers are planted as seed and therefore the plant and the next generation of tubers become infected, albeit not always for the full 100% (Bertschinger et al., 2017).

Primary infection can only occur through transmission of virus. Aphids are the main vectors spreading virus diseases like PLRV and *Potato virus A* (PVA), whereas PVX is only transmitted mechanically. PVY, *Potato virus S* (PVS) and *Potato virus M* (PVM) can be transmitted in both ways (de Bokx and van der Want, 1987; Salazar, 1996; Struik and Wiersema, 1999).

In general, PLRV and PVX infections show severe visual symptoms (upward rolling of leaflets for PLRV; stunting, mosaic patterns on leaflets for both PLRV and PVX), PVY and PVA infections show mild visual symptoms (mild mosaic, tip necrosis), and PVS and PVM infections are usually symptomless (Loebenstein et al., 2001). However, visual symptoms can vary depending on cultivar, virus strain, synergisms in mixed infections, and environmental conditions (Döring, 2011).

To overcome the existing constraint of poor seed quality in Eastern Africa a seed degeneration management technology, known as positive selection, was found to be highly effective in increasing the low tuber yield; this technology was associated with reduced virus incidence for PLRV, PVX and PVY (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012). When carrying out positive selection, the healthiest looking plants in ware potato crops are pegged and selected just before full flowering to identify plants of which tubers will serve as seed for the next season (Gildemacher et al., 2007). Two weeks after selecting, the positive-selected plants have to be checked for being still without symptoms. At harvest, tubers from selected plants are separately collected from those of non-selected plants, and used in the next season as seed tubers for the next crop, after checking their health status visually and selecting the appropriate size. In this way, the best looking tubers from the healthiest-looking plants are planted in the next season and are expected to produce relatively healthy plants and progeny tubers, with reduced virus infection, and increased yield potential compared with standard farmers' procedures of seed selection (Schulte-Geldermann et al., 2012).

To the best of our knowledge, until now, literature reports on positive seed selection were limited to investigations including only one growing cycle of multiplication and three viruses (PLRV, PVX, PVY). The current research focuses on examining and understanding positive selection for maintaining quality of the seed potato stock or even for its regeneration across multiple cycles and in addition for six viruses (PLRV, PVX, PVY, PVA, PVS, and PVM), differing in severity of symptoms and method of transmission. Different locations of seed production, various sources of seed and different cultivars were included in the field experiments.

The objectives of this study were to analyse how the incidence of contrasting viruses across several seasons of multiplication changes using different seed selection methods (positive selection, farmers' selection) under the climatic conditions in southwestern Uganda and in seed lots from different origin and starting quality. Specific research questions were (1) whether positive selection across several field generations could lead to a reduction in virus infection (regeneration) in different seed lots; (2) whether positive selection could maintain a high health status of tubers when healthy 3G[1] seed tubers from the national Ugandan research station are used; and (3) whether seeds from positive selection have a reduced virus incidence compared to those from farmers' selection. Knowledge acquired in this research can contribute to a deeper understanding of the dynamics of viral diseases in the potato crop and of the role of positive selection in reducing seed degeneration. Such knowledge could also help to sustainably improve the availability of (high) quality seed tubers in Uganda and other East African countries by own-produced seed. It could also help to design alternative seed systems suitable for low-income countries with limited opportunities to implement strict seed certification schemes.

3.2. Materials and methods

3.2.1. Experimental design

Three multi-season field experiments were carried out across four production seasons at three locations in the Kabale district in the main potato production region of southwestern Uganda. Details of all locations and experiments are presented in Table 3.1. For the first two experiments, two high-quality

[1] 3G seed (also called Basic Seed) refers to three generations of multiplying, starting from in-vitro culture and thereafter being multiplied in the greenhouse and in the field. Currently, 3G seed can be purchased from the national research institute KAZARDI in Uganda.

3G seed tuber lots were obtained from the Kachwekano Zonal Agricultural Research and Development Institute (KAZARDI), one seed tuber lot from cv. Victoria and one seed tuber lot from cv. Katchpot 1. Experiment 1, with both seed lots, was planted in the fields of the research station KAZARDI located in Karengyere (2433 m a.s.l.); Experiment 2, with the same seed lots, was planted in the fields of the research station in Kabale (2246 m a.s.l.). In Experiment 3, three seed sources were used: a. 4G seed potatoes from the Ugandan National Seed Potato Production Association (UNSPPA), cv. Victoria; b. seed potatoes from the local market (unknown generation) of cv. Victoria; and c. 5G seed potatoes from a local farm which saved seed potatoes for own use, cv. Rwangume. Experiment 3, with these three seed sources, was planted in the fields of a local farm in Hamurwa (2220 m a.s.l.).

Planting took place in four subsequent seasons: October 2013 (1^{st} season 2013 Long Rainy Season (LRS)), April 2014 (2^{nd} season 2014 Short Rainy Season (SRS)), October 2014 (3^{rd} season 2014-LRS), and April 2015 (4^{th} season 2015-SRS). Two growing seasons in one calendar year were used because of the two rainy seasons (LRS and SRS) in this region and because planting potato in both seasons is a common practice in Kabale district (Gildemacher et al. 2009).

The experiments had a split-plot design with the seed potato lot as main factor and the seed selection method as a sub factor in three replicated blocks. In the experiments four seed selection methods were applied: a. positive selection (PS) in all seasons (further referred to as PS-PS-PS), b. farmers' selection (FS) in all seasons (further referred to as FS-FS-FS), c. alternating seed selection in the seasons starting with positive selection in the 1^{st} season (further referred to as PS-FS-PS), and d. alternating seed selection in the seasons starting with farmers' selection in the 1^{st} season (further referred to as FS-PS-FS) (Figure 3.1). The 4^{th} season is lacking in these codes because that season was used to assess the quality of the tubers produced in the previous seasons. Because some treatments only started to differ later in the 2^{nd} season, the data on the 1^{st} season presented in Table 3.2 are based on the double number of plots.

Table 3.1. Information on the three experimental sites in Kabale district

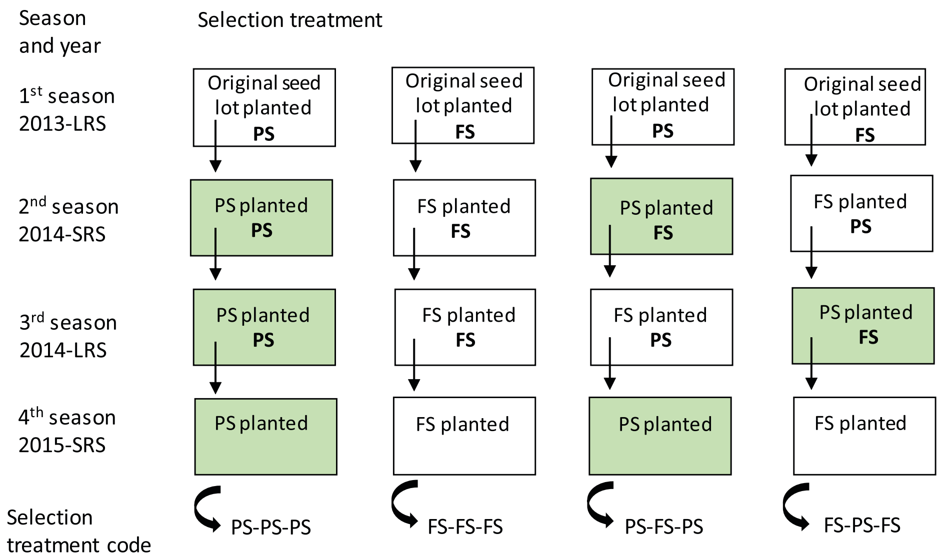
	Experiment 1	Experiment 2	Experiment 3
Location	Karengyere	Kachwekano	Hamurwa
Elevation	2433 m asl	2246 m asl	2220 m asl
Longitude	29°47'57 E	29°56'5 E	29°54'56 E
Latitude	1°14'08 S	1°15'26 S	1°06'58 S
Soil	Ferralsols	Ferralsols	Ferralsols
Fertilisation	45 kg N/ ha	45 kg N/ ha	45 kg N/ ha
Seed spacing (between row × within row)	70 × 30 cm	70 × 30 cm	70 × 30 cm
Seed lots (Seed Source and Potato Cultivar)	3G KAZARDI/ cv. Victoria 3G KAZARDI/ cv. Katchpot 1	3G KAZARDI/ cv. Victoria 3G KAZARDI/ cv. Katchpot 1	4G UNSPPA/ cv. Victoria Local market/ cv. Victoria 5G Farm-saved seed/ cv. Rwangume
Selection treatments	PS[a] and FS[b]	PS and FS	PS and FS
Storage (all seasons)	DLS[c] on wooden shelves	Wooden shed (dark) on wooden shelves	DLS on wooden shelves
Selection of seed tubers	Before planting	Before planting	Before planting
1st season: 2013- LRS[d]			
Planting date	03.10.2013	04.10.2013	05.10.2013
Average temperature in the growing period (°C)	Not available	18.8	Not available
Total rainfall in the growing period (mm)	83.5 (excl. 2013)	107.4	Not available
Flowering and PS date 1st season	15.12.2013 (73 DAP[e])	15.12.2013 (72 DAP)	16.12.2013 (72 DAP)
Leaf sampling date 1st season	15.12.2013 (73 DAP)	-	16.12.2013 (72 DAP)
Haulm destruction date 1st season	21.01.2013 (110 DAP)	23.01.2013 (111 DAP)	21.01.2013 (108 DAP)
Harvest date 1st season	29.01.2014 (118 DAP)	30.01.2014 (118 DAP)	31.01.2014 (118 DAP)
Other cultural practices 1st season	Ploughing (2 ×) Herbicide Glyphosate a.i. 360g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (4×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (6×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (4×)
Neighbouring crops	Potato, sorghum, wheat	Potato, sweet potato, beans	Sweet potato, beans, sorghum, maize, potato

2nd season: 2014- SRS[f]			
Planting date	07.04.2014 (69 DAH[g])	06.04.2014 (67 DAH)	08.04.2014 (68 DAH)
Average temperature in the growing period (°C)	Not available	18.5	Not available
Total rainfall in the growing period (mm)	183.6	61.2	Not available
Leaf sampling date 2nd season	01.05.2014 (24 DAP)	01.05.2014 (25 DAP)	02.05.2014 (24 DAP)
Flowering and PS date 2nd season	12.06.2014 (65 DAP)	11.06.2014 (64 DAP)	12.06.2014 (64 DAP)
Haulm destruction date 2nd season	17.07.2014 (100 DAP)	19.07.2014 (103 DAP)	21.07.2014 (103 DAP)
Harvest date 2nd season	28.07.2014 (111 DAP)	29.07.2014 (113 DAP)	30.07.2014 (112 DAP)
Other cultural practices 2nd season	Ploughing (2×) Weeding, incl. hilling up (2×) Spraying (against *Phytophthora infestans*) (3×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Spraying (against *Phytophthora infestans*) (3×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Spraying (against *Phytophthora infestans*) (4×)
Neighbouring crops	Potato, sorghum, wheat	Sweet potato, beans, sorghum, maize, potato	Beans, sorghum, maize, potato
3rd season: 2014- LRS			
Planting date	10.10.2014 (75 DAH)	09.10.2014 (73 DAH)	11.10.2014 (74 DAH)
Average temperature in the growing period (°C)	Not available	18.6	Not available
Total rainfall in the growing period (mm)	250.4	197.5	Not available
Leaf sampling date 3rd season	05.11.2014 (26 DAP)	05.11.2014 (27 DAP)	06.11.2014 (26 DAP)
Flowering and PS date 3rd season	18.12.2014 (69 DAP)	17.12.2014 (69 DAP)	18.12.2014 (68 DAP)
Haulm destruction date 3rd season	28.01.2015 (110 DAP)	27.01.2015 (110 DAP)	26.01.2015(107 DAP)
Harvest date 3rd season	03.02.2015 (116 DAP)	02.02.2015 (116 DAP)	04.02.2015 (116 DAP)
Other cultural practices 3rd season	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (7×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (6×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (8×)
Neighbouring crops	Potato, peas, sorghum	Beans, sweet potato, potato	Sorghum, maize, beans, potato, sweet potato,

4th season: 2015- SRS			
Planting date	16.04.2015 (73 DAH)	14.04.2015 (72 DAH)	15.04.2015 (71 DAH)
Average temperature in the growing period (°C)	Not available	18.4	Not available
Total rainfall in the growing period (mm)	227.8	156.2	Not available
Leaf sampling date 4th season	14.05.2015 (28 DAP)	14.05.2015 (30 DAP)	15.05.2015 (30 DAP)
Flowering and PS date 4th season	18.06.2015 (63 DAP)	17.06.2015 (64 DAP)	18.06.2015 (64 DAP)
Haulm destruction date 4th season	21.07.2015 (96 DAP)	23.07.2015 (100 DAP)	23.07.2015 (99 DAP)
Harvest date 4th season	04.08.2015 (110 DAP)	06.08.2015 (114 DAP)	07.08.2015 (114 DAP)
Other cultural practices 4th season	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (7×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (8×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (8×)
Neighbouring crops	Potato, sorghum	Sweet potato, beans, sorghum, potato	Sweet potato, beans, sorghum, maize

[a]PS, Positive Selection
[b]FS, Farmers' Selection
[c]DLS, Diffuse Light Storage
[d]LRS, Long rainy season
[e]DAP, Days after Planting
[f]SRS, Short rainy season
[g]DAH, Days after Harvest

In one gross experimental plot, 60 tubers were planted in 6 rows with a row spacing of 70 cm and a seed spacing within the row of 30 cm; for the net plot the border plants in the outer rows were excluded, so in total 40 tubers or plants in the net plot were used for the assessment. In the PS treatment, in total 15 plants from the 40 tubers in the net plot were selected for positive selection, which accounts for plants from 37.5% of all seed tubers planted in the net plot. The harvest of those 15 plants was needed to achieve enough medium-sized seed potatoes for the next planting season under the conditions in Kabale district in southwestern Uganda. Under PS the 15 best looking



LRS, Long Rainy Season
SRS, Short Rainy Season
PS, Positive Selection
FS, Farmers' Selection
PS/FS, Selection was applied in this season

Figure 3.1. Scheme of selection treatments (in green when positive selection seed was planted) in the three experiments over the seasons.

plants in the plot were selected just before full flowering (65 - 73 DAP) and those plants were checked again two weeks later (Table 3.1). In the FS plots, plants were not selected during crop growth and medium-sized seed tubers were selected by farmers at planting time from the stored tuber bulk of the former harvest. In the PS treatments, plants were selected during crop growth and seed tuber selection was done by farmers by selecting medium-sized seed tubers from these PS plants after storage at planting time. For each of the four treatments, the replicated plots were combined before selecting the seed tubers.

Fertilisation was done with 45 kg N/ha at planting in each season, based on NPK 17:17:17 and further crop management was done according to general recommendations to farmers (Table 3.1).

3.2.2. Sampling method of plants and tubers for virus testing

To assess the virus incidence in the crops grown from the original seed lots and to assess the virus incidence in the plants selected for positive selection, leaves were sampled in the 1st season in Experiments 1 and 3 at the day of PS, which was just before full flowering. In the plots receiving positive selection, leaves were sampled from 10 of the 15 positive selected plants. For the plots where no selection took place (FS plots) samples were taken from 10 random plants per net plot. These samples represent both the virus status of the crops from the original seed lot and the virus status of the plants used for FS and PS.

To determine the virus status of the tubers produced in the different treatments during the 1st, 2nd and 3rd seasons, leaf samples of 10 plants were taken in each net plot from the newly emerged plants from these tubers in the 2nd, 3rd and 4th season, respectively, when plantlets were approximately 15 cm tall.

The leaf sample per plant consisted of three leaflets, one from each of the upper three leaves. Those three leaflets were combined in one sampling bag. All leaf samples were transported by airplane in a cardboard box to the Netherlands within 2 days, stored at -80 ˚C and analysed for virus infection at the end of the experiments. All leaf samples were destroyed after analyses were concluded.

3.2.3. Assessing virus infection

To assess the virus incidence in crops and PS selected plants from the original seed lots in the 1st season, the infection by PLRV, PVX, PVY, PVA, PVS, and PVM in each of 10 plants per plot was assessed with DAS-ELISA according to a standard protocol (Prime Diagnostics) with polyclonal antibodies obtained from Prime Diagnostics® (www.primediagnostics.com).

To assess the virus incidence in the seed tubers produced in a season, leaves from 10 newly emerged (in the next season) plants per net plot were assessed with the LUMINEX xMAP technology (van der Vlugt et al., 2015) according to the standard protocol (www.primediagnostics.com). Samples were tested for six potato viruses PLRV, PVX, PVY, PVA, PVS, and PVM simultaneously with a Luminex xMAP kit based on DAS-ELISA polyclonal antibodies supplied by Prime Diagnostics® (www.primediagnostics.com). Samples were considered virus positive when values for optical density at 405 nm (OD 405) in ELISA or xMAP Mean Fluorescent Intensities (MFIs) were higher than the total of the average of six negative controls plus three times the standard deviation of the negative controls.

We compared DAS-ELISA and LUMINEX in numerous samples and the two methods produced the same results and the same sensitivity. If a sample was free of the viruses tested, this plant was considered as clean.

3.2.4. Haulm removal, tuber harvest and tuber storage

Haulm removal was done manually between 96 to 111 days after planting when plants had reached final maturity (Table 3.1). At harvest, between 111 to 118 days after planting (Table 3.1), all tubers from the selected plants in plots receiving PS were separately harvested. During storage, the individual replicates of one treatment were combined and stored separately from the tubers of the other treatments. In plots receiving FS in a given season, all tubers were harvested.

All tubers were stored on wooden shelves either in a dark wooden shed (Experiment 2) or in a diffused light storage (Experiments 1 and 3), all with insecticide a.i. Malathion 57% sprinkled on top and covered with grass locally called "Kikuyu" (*Pennisetum clandestinum*) and couch grass (*Digitaria abyssinica*). Storage duration of the tubers was between 69 and 75 days (Table 3.1).

3.2.5. Monitoring aphid abundance and weather data

To monitor aphid pressure three yellow water traps were placed in the middle of each of the three blocks in each experiment in Seasons 2 to 4. Rectangular yellow plastic traps (35.0 cm × 25.0 cm × 8.0 cm; $l \times w \times h$) were filled to two thirds with tap water and a small amount of dish washer detergent added to decrease surface tension. Traps were installed in the fields after sampling of the leaves of the emerged plants in order to avoid possible early attraction and influx of aphids. Aphids were collected weekly and counted, but no distinction was made between species (Figure 3.2).

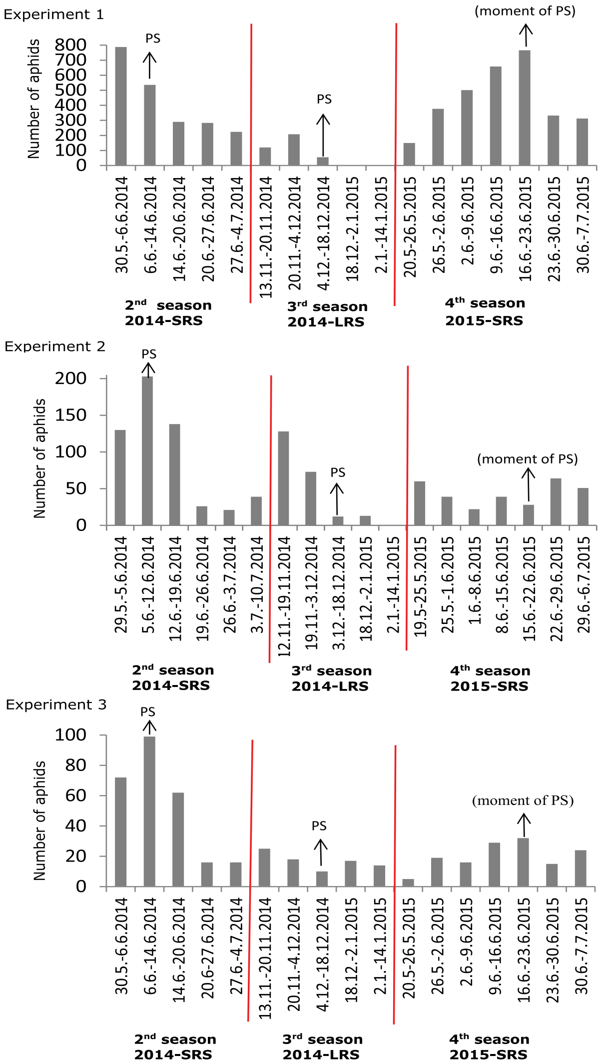


Figure 3.2. Seasonal aphid catches during the three experimental periods (growing period 2nd season 2014-SRS, 3rd season 2014-LRS, and 4th season 2015-SRS) (red lines indicate the next growing period). Aphid data were not recorded in the 1st season.

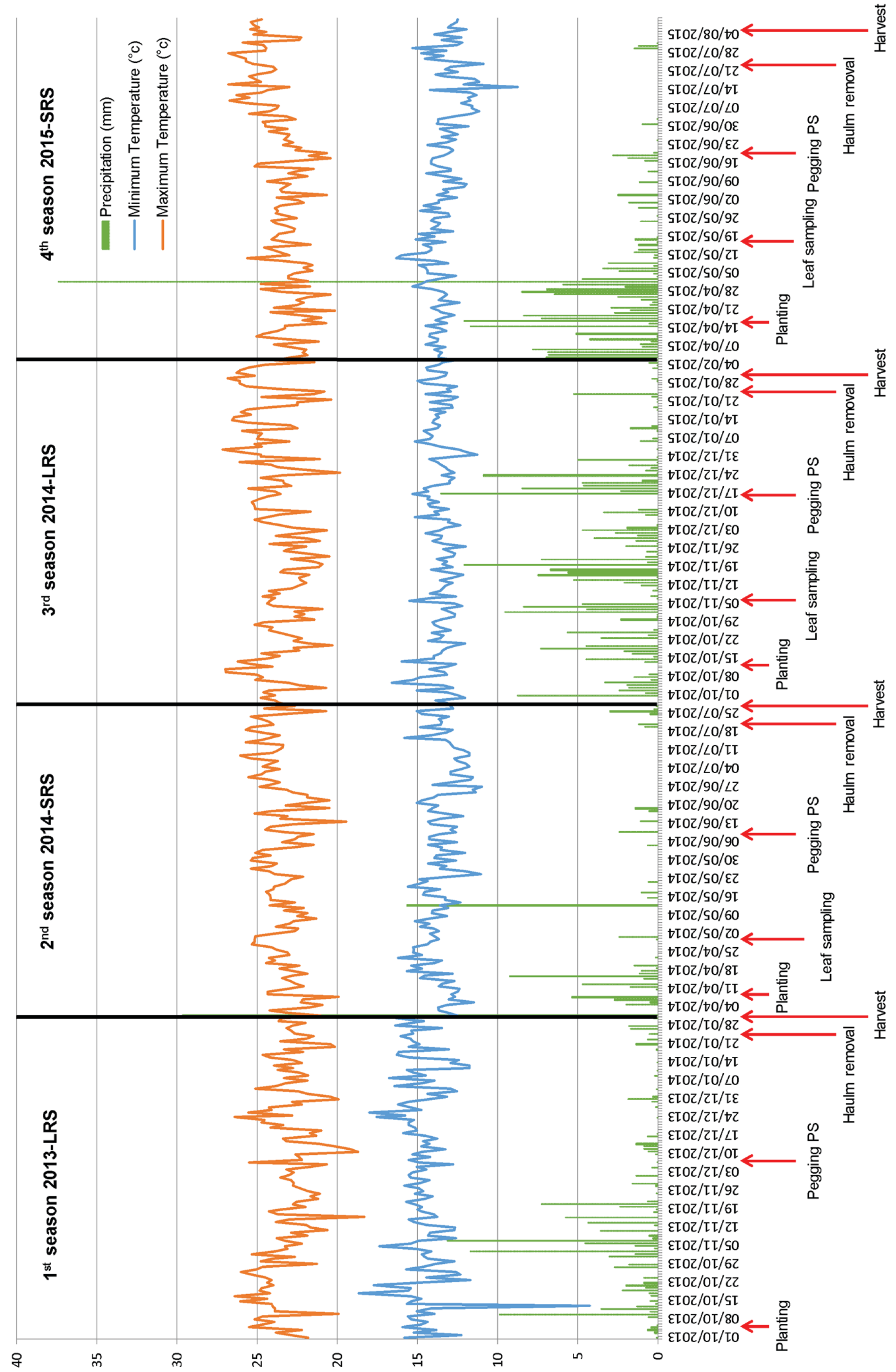


Figure 3.3. Weather data of Experiment 2 during the growing periods with important crop and experiment management practices (black lines indicate the next season)

Table 3.2. Virus incidence (% infected plants) in the full crops and selected plants at the moment the first selection took place in the 1st season (2013-LRS) before full flowering and virus incidence in the tubers produced from these crops as assessed in the emerged plants in the 2nd season (2014-SRS) (in parentheses angular transformed data of the proportions)

Seed lot	Selection treatment	Clean	Virus incidence (%)					
			PLRV	PVX	PVY	PVA	PVS	PVM
Experiment 1								
Assessment at BFF[a] 2013-LRS								
3G/Cv. Victoria	Plants for FS[b]	5 (7.5 a)	20 (17.0 a)	23 (18.9 a)	5 (5.5 a)	0 (0.0 a)	95 (82.5 a)	63 (58.1 a)
	Plants for PS[c]	13 (12.9 a)	2 (3.1 a)	10 (16.0 a)	0 (0.0 a)	2 (3.1 a)	87 (77.1 a)	55 (48.1 a)
3G/Cv. Katchpot 1	Plants for FS	75 (60.5 b)	3 (6.1 a)	7 (8.9 a)	2 (3.1 a)	2 (3.1 a)	17 (29.5 b)	25 (23.6 a)
	Plants for PS	68 (56.3 b)	0 (0.0 a)	0 (0.0 a)	0 (0.0 a)	0 (0.0 a)	32 (33.7 b)	30 (32.6 a)
Significances								
$P_{\text{Selection treatment (ST)}}$		0.912	0.051	0.051	0.199	1.000	0.912	0.953
$P_{\text{Seed lot (SL)}}$		**0.023**	0.423	0.423	0.423	-	**0.023**	0.264
$P_{\text{ST × SL}}$		0.392	0.419	0.301	0.704	0.183	0.392	0.273
Assessment at Emergence 2014-SRS								
3G/Cv. Victoria	FS	2 (3.1 a)	62 (56.9 a)	65 (54.9 a)	8 (15.4 a)	22 (26.9 a)	98 (86.9 a)	90 (75.6 a)
	PS	2 (3.1 a)	48 (43.6 a)	57 (48.5 a)	7 (12.3 a)	15 (20.5 a)	98 (86.9 a)	88 (75.0 a)
3G/Cv. Katchpot 1	FS	35 (33.5 b)	45 (41.4 a)	28 (31.9 b)	10 (16.4 a)	12 (18.1 a)	37 (36.5 b)	27 (30.4 b)
	PS	42 (39.6 b)	45 (42.5 a)	22 (27.4 b)	5 (7.5 a)	8 (13.6 a)	40 (39.0 b)	38 (38.0 b)
Significances across seasons								
$P_{\text{Selection treatment (ST)}}$		0.607	**0.023**	**0.016**	**0.037**	0.254	0.923	0.696
$P_{\text{Season (S)}}$		0.079	0.094	0.078	0.172	**0.013**	0.174	0.257
$P_{\text{Seed lot (SL)}}$		**0.002**	0.163	0.586	0.513	0.408	**<0.001**	**0.020**
$P_{\text{ST × S}}$		0.729	0.965	0.903	0.700	0.254	0.799	0.619
$P_{\text{ST × SL}}$		0.810	0.168	0.651	0.700	0.656	0.403	0.169
$P_{\text{S × SL}}$		0.245	0.888	0.586	0.912	0.408	0.902	0.411
$P_{\text{ST × S × SL}}$		0.276	0.752	0.381	0.372	0.390	0.617	0.521
Experiment 3								
Assessment at BFF 2013-LRS								
4G UNSPPA/Cv. Victoria	Plants for FS	0 (0.0 a)	2 (3.1 a)	5 (7.5 a)	0 (0.0 a)	5 (5.5 a)	100 (90.0 b)	65 (56.4 b)
	Plants for PS	2 (3.1 a)	2 (3.1 a)	2 (3.1 a)	2 (3.1 a)	2 (3.1 a)	98 (86.9 b)	85 (71.4 b)
Market/Cv. Victoria	Plants for FS	0 (0.0 a)	8 (10.0 a)	3 (6.1 a)	2 (3.1 a)	7 (10.6 a)	100 (90.0 b)	78 (70.0 b)
	Plants for PS	2 (3.6 a)	7 (6.5 a)	2 (3.1 a)	3 (4.4 a)	3 (4.4 a)	98 (86.9 b)	72 (63.6 b)
5G Farm saved/Cv. Rwangume	Plants for FS	28 (42.9 b)	7 (12.3a)	8 (18.1 a)	2 (3.1a)	7 (8.6a)	32 (33.6 a)	12 (18.1 a)
	Plants for PS	31 (46.5 b)	8 (10.0a)	17 (19.6 a)	2 (3.1a)	2 (3.1a)	33 (34.2 a)	15 (18.6 a)
Significances								
$P_{\text{Selection treatment (ST)}}$		0.162	0.619	0.661	0.560	0.201	0.602	0.548
$P_{\text{Seed lot (SL)}}$		**<0.001**	0.424	0.139	0.677	0.806	**<0.001**	**0.012**
$P_{\text{ST × SL}}$		0.994	0.932	0.853	0.881	0.903	0.840	0.222
Assessment at emergence 2014-SRS								
4G UNSPPA/Cv. Victoria	FS	0 (0.0 a)	58 (52.9 a)	43 (38.5 ab)	35 (31.4 a)	0 (0.0 a)	100 (90.0 b)	77 (62.3 b)
	PS	2 (3.1 a)	50 (44.6 a)	30 (30.1 ab)	10 (11.0 a)	0 (0.0 a)	98 (86.9 b)	82 (65.0 b)
Market/Cv. Victoria	FS	0 (0.0 a)	58 (54.6 a)	28 (22.6 a)	30 (32.5 a)	0 (0.0 a)	100 (90.0 b)	70 (61.9 b)
	PS	0 (0.0 a)	45 (42.1 a)	12 (14.0 a)	20 (21.5 a)	0 (0.0 a)	100 (90.0 b)	67 (55.3 b)
5G Farm saved/Cv. Rwangume	FS	3 (6.1 a)	62 (52.5 a)	38 (38.0 b)	7 (10.6 a)	0 (0.0 a)	90 (77.0 a)	18 (20.5 a)
	PS	27 (30.1 b)	48 (39.0 a)	27 (28.3 b)	3 (6.1 a)	0 (0.0 a)	67 (56.0 a)	10 (11.0 a)
Significances across seasons								
$P_{\text{Selection treatment (ST)}}$		**<0.001**	**0.035**	0.141	0.161	0.193	**0.024**	0.848
$P_{\text{Season (S)}}$		0.083	0.138	**0.041**	0.066	0.186	**0.022**	0.536
$P_{\text{Seed lot (SL)}}$		**<0.001**	0.855	**0.018**	0.277	0.802	**<0.001**	**0.004**
$P_{\text{ST × S}}$		0.151	0.127	0.347	0.075	0.193	0.149	0.328
$P_{\text{ST × SL}}$		**0.004**	0.841	0.964	0.770	0.903	0.212	0.210
$P_{\text{S × SL}}$		**<0.001**	0.855	0.150	0.290	0.802	**0.001**	0.932
$P_{\text{ST × S × SL}}$		**0.040**	0.960	0.540	0.569	0.903	**0.043**	0.786

Values in ***bold*** indicate significant difference, different *letters* indicate significant difference between means according to Fishers protected LSD test at 5% level

[a]BFF= Before Full Flowering

[b]FS= Farmers' Selection

[c]PS= Positive Selection

-: *P* value could not be obtained because of 0% infection in PVA in all treatments

Weather data was derived from the internet platform awhere (awhere.com) for Experiment 2 (Figure 3.3); for Experiment 1, manually monitored rain data were recorded at the KAZARDI station in Karengyere (Table 3.1). No reliable weather data were available for Experiment 3.

3.2.6. Statistical analysis

Data were analysed using GenStat for Windows 18th Edition (VSN International, 2016). General Analysis of Variance was used to test the effect of the factors selection method, season and seed lot and their interactions on incidence of the individual viruses and the proportion of plants free of virus. The proportions of the data of the virus incidence were angular transformed before analysis (Fernandez, 1992). When proportions were equal to 0 or 1 a replacement was done by (1/4n) and [1-(1/4n)] respectively, where n represents the total number of leaf samples per net plot (Fernandez, 1992).

The data from the plants and tubers produced in the first season (Table 3.2) were analysed based on the double number of plots because the two alternating treatments (PS-FS-PS and FS-PS-FS) only started to differ from the two consistent treatments (PS-PS-PS and FS-FS-FS) from the end of the second season onwards. In the analysis, contrasts between the four selection treatments across multiple seasons were used to test for differences between individual selection treatments. Where the *P*-value in the ANOVA showed significant effects or interactions ($P<0.05$) Fishers Protected Least Significant Difference (LSD) test at $\alpha=0.05$ was applied.

3.3. Results

Figure 3.4 and 3.5 show in detail the effects of the selection treatments on incidence of the individual viruses in successive seasons, in the different seed lots and experiments. Table 3.3 shows the accompanying ANOVA analysis with significances of the effects of the factors a) selection treatment, b) season, c) seed lot, and their interactions. For the factor selection treatment, also the contrasts between the individual selection treatments were tested because in part of the selection treatments the applied selection method varied over the seasons, thereby increasing the variation of the main effect. For the factor season, the significance of a linear component was tested indicating if there was a significant increase or decrease in virus incidence across multiple seasons of selection. No significant three-way interactions were found in any of the experiments. Table 3.4 shows the effects of the selection treatments across seasons and seed lots in the three experiments. Results of virus incidences are first described for the proportion of clean plants (tested negative for all viruses tested) and thereafter for viruses giving severe visible symptoms (PLRV and PVX), followed by mild visual symptoms (PVY and PVA) and weak visual symptoms (PVS and PVM).

3.3.1. Effects of selection treatments on virus incidence

Continuously positive selection (PS-PS-PS) in general decreased the virus incidence compared to continuously farmers' selection (FS-FS-FS) (Table 3.4; Figure 3.5). The treatment with PS in two of the three seasons (PS-FS-PS) usually outperformed (when different) the treatment with PS in only one of the three seasons (FS-PS-FS); however, differences between them were hard to be assessed as statistically significant (Table 3.3).

The percentage of clean plants was higher in the PS-PS-PS treatment than in the FS-FS-FS treatment for cv. Katchpot 1 and cv. Rwangume (Figure 3.4), with the differences being significant in Experiments 2 and 3 (Table 3.4). The relative increase of clean plants by PS-PS-PS treatment compared to FS-FS-FS treatment was 47% in Experiment 3 and 37 % in Experiment 2 (Table 3.4). In the farm-saved seed lot of cv. Rwangume an increase in time in the proportion of clean tubers took place. In the PS-PS-PS treatment 93% of the tubers were clean after 3 seasons of selection, in the FS-FS-FS treatment 67%. In cv. Victoria almost no clean plants were found in all three experiments.

The decrease in virus incidence by continuously positive selection (PS-PS-PS) compared to continuously farmers selection (FS-FS-FS) was statistically significant for PLRV and PVX in all experiments (Table 3.3); a relative decrease up to 35% and 34%, respectively, was achieved (Table

Table 3.3. P-values of the F ratios from ANOVA for the effects of selection treatment, season, and seed lot and their interactions in the three experiments

		Virus					
Factors and contrasts	Clean	PLRV	PVX	PVY	PVA	PVS	PVM
Experiment 1							
Selection treatment	0.305	0.137	**0.018**	0.131	**0.025**	0.999	0.993
PS-PS-PS vs FS-FS-FS	0.084	**0.037**	**0.009**	**0.040**	**0.046**	0.972	0.958
PS-PS-PS vs PS-FS-PS	0.128	0.121	**0.011**	0.322	0.659	0.987	0.891
PS-PS-PS vs FS-PS-FS	0.293	0.053	**0.007**	0.050	**0.008**	0.910	0.884
PS-FS-PS vs FS-FS-FS	0.827	0.563	0.923	0.267	0.113	0.958	0.850
PS-FS-PS vs FS-PS-FS	0.627	0.684	0.856	0.312	**0.024**	0.896	0.777
FS-PS-FS vs FS-FS-FS	0.482	0.863	0.923	0.920	0.468	0.938	0.925
Season	0.751	0.458	0.607	0.172	**0.006**	**0.033**	0.154
Linear change season	0.895	0.576	0.636	0.662	**0.035**	**0.023**	0.136
Seed lot	**<0.001**	0.200	**0.004**	0.749	0.281	**<0.001**	**<0.001**
Selection treatment × Season	0.150	0.736	0.965	0.912	0.232	0.160	0.376
PS-PS-PS vs FS-FS-FS × Linear Season	0.444	0.983	0.803	0.868	0.428	0.236	0.068
PS-PS-PS vs PS-FS-PS × Linear Season	0.248	0.897	0.965	0.892	0.799	0.212	0.308
PS-PS-PS vs FS-PS-FS × Linear Season	0.125	0.494	0.768	0.800	0.289	**0.042**	**0.048**
PS-FS-PS vs FS-FS-FS × Linear Season	0.691	0.881	0.836	0.976	0.589	0.948	0.402
PS-FS-PS vs FS-PS-FS × Linear Season	0.694	0.420	0.801	0.906	0.418	0.410	0.316
FS-PS-FS vs FS-FS-FS × Linear Season	0.431	0.511	0.964	0.930	0.786	0.374	0.867
Selection treatment × Seed lot	0.066	0.873	0.470	0.966	0.775	0.053	**0.003**
PS-PS-PS vs FS-FS-FS × Seed lot	0.439	0.409	0.228	0.786	0.916	0.460	0.114
PS-PS-PS vs PS-FS-PS × Seed lot	0.228	0.662	0.960	0.615	0.937	0.987	0.562
PS-PS-PS vs FS-PS-FS × Seed lot	**0.010**	0.661	0.815	0.747	0.365	0.051	**0.022**
PS-FS-PS vs FS-FS-FS × Seed lot	0.661	0.696	0.247	0.816	0.979	0.450	**0.034**
PS-FS-PS vs FS-PS-FS × Seed lot	0.143	0.999	0.777	0.856	0.408	0.053	0.078
FS-PS-FS vs FS-FS-FS × Seed lot	0.060	0.697	0.152	0.959	0.422	**0.009**	**<0.001**
Season × Seed lot	0.910	0.050	0.696	0.146	0.347	0.063	0.510
Linear Season × Seed lot	0.985	0.988	0.477	0.231	0.200	**0.029**	0.458
Selection treatment × Season × Seed lot	0.635	0.820	0.878	0.777	0.564	0.858	0.386
PS-PS-PS vs FS-FS-FS × Linear Season × Seed lot	0.660	0.830	0.787	0.361	0.428	0.740	0.707
PS-PS-PS vs PS-FS-PS × Linear Season × Seed lot	0.398	0.744	0.519	0.844	0.374	0.641	0.789
PS-PS-PS vs FS-PS-FS × Linear Season × Seed lot	0.649	0.628	0.559	0.726	0.715	0.719	0.460
PS-FS-PS vs FS-FS-FS × Linear Season × Seed lot	0.683	0.832	0.362	0.471	0.923	0.426	0.914
PS-FS-PS vs FS-PS-FS × Linear Season × Seed lot	0.635	0.267	0.952	0.878	0.213	0.410	0.316
FS-PS-FS vs FS-FS-FS × Linear Season × Seed lot	0.988	0.196	0.394	0.570	0.249	0.977	0.267
Experiment 2							
Selection treatment	**0.018**	**0.001**	**0.007**	0.507	0.204	0.057	0.580
PS-PS-PS vs FS-FS-FS	**0.024**	**<0.001**	**0.001**	0.295	0.091	0.135	0.205
PS-PS-PS vs PS-FS-PS	0.662	0.125	0.527	0.432	0.642	0.617	0.879
PS-PS-PS vs FS-PS-FS	**0.009**	**0.049**	0.430	0.144	0.756	0.220	0.631
PS-FS-PS vs FS-FS-FS	0.063	**0.009**	**0.008**	0.789	0.214	**0.050**	0.263
PS-FS-PS vs FS-PS-FS	**0.025**	0.644	0.875	0.488	0.446	0.462	0.743
FS-PS-FS vs FS-FS-FS	0.679	**0.027**	**0.012**	0.669	**0.049**	**0.009**	0.425
Season	0.980	0.653	0.248	0.559	0.205	0.297	0.067
Linear change season	0.955	0.461	0.116	0.594	0.094	0.175	**0.025**
Seed lot	**<0.001**	**0.002**	**0.009**	0.490	0.555	**<0.001**	**<0.001**
Selection treatment × Season	**0.042**	**<0.001**	0.060	0.256	0.869	0.230	0.282
PS-PS-PS vs FS-FS-FS × Linear Season	0.073	**0.040**	**0.029**	0.552	0.338	0.145	0.155
PS-PS-PS vs PS-FS-PS × Linear Season	**0.018**	0.471	0.413	0.462	0.714	**0.023**	0.127
PS-PS-PS vs FS-PS-FS × Linear Season	0.922	**0.021**	0.756	0.588	1.000	0.067	0.853

PS-FS-PS vs FS-FS-FS × Linear Season	0.523	0.170	0.156	0.188	0.188	0.384	0.913
PS-FS-PS vs FS-PS-FS × Linear Season	**0.022**	**0.003**	0.610	0.845	0.714	0.632	0.089
FS-PS-FS vs FS-FS-FS × Linear Season	0.089	**<0.001**	0.057	0.259	0.338	0.693	0.110
Selection treatment × Seed lot	0.212	0.980	0.973	0.891	0.971	0.509	**0.014**
PS-PS-PS vs FS-FS-FS × Seed lot	0.145	0.940	0.858	0.608	0.738	0.394	0.205
PS-PS-PS vs PS-FS-PS × Seed lot	0.662	0.805	0.896	0.548	0.642	0.617	0.615
PS-PS-PS vs FS-PS-FS × Seed lot	0.065	0.790	0.784	0.468	0.765	0.508	**0.037**
PS-FS-PS vs FS-FS-FS × Seed lot	0.302	0.748	0.757	0.929	0.895	0.180	0.080
PS-FS-PS vs FS-PS-FS × Seed lot	0.152	0.985	0.885	0.900	0.867	0.248	0.107
FS-PS-FS vs FS-FS-FS × Seed lot	0.679	0.733	0.650	0.830	0.972	0.848	**0.001**
Season × Seed lot	0.401	0.556	0.948	0.342	0.192	0.635	0.157
Linear Season × Seed lot	0.228	0.591	0.900	0.162	0.118	0.453	0.742
Selection treatment × Season × Seed lot	0.977	0.979	0.684	0.772	0.821	0.385	0.708
PS-PS-PS vs FS-FS-FS × Linear Season × Seed lot	0.441	0.735	0.390	0.190	0.680	0.505	0.155
PS-PS-PS vs PS-FS-PS × Linear Season × Seed lot	0.722	0.880	0.141	0.668	0.276	0.464	0.127
PS-PS-PS vs FS-PS-FS × Linear Season × Seed lot	0.922	0.801	0.545	0.533	1.000	0.210	0.537
PS-FS-PS vs FS-FS-FS × Linear Season × Seed lot	0.676	0.851	0.530	0.373	0.137	0.948	0.913
PS-FS-PS vs FS-PS-FS × Linear Season × Seed lot	0.649	0.267	0.952	0.878	0.213	0.410	0.316
FS-PS-FS vs FS-FS-FS × Linear Season × Seed lot	0.500	0.555	0.798	0.484	0.680	0.059	0.411
Experiment 3							
Selection treatment	**<0.001**	**0.001**	0.108	0.097	**0.043**	**0.004**	0.216
PS-PS-PS vs FS-FS-FS	**<0.001**	**0.001**	**0.017**	0.075	0.119	**0.014**	**0.050**
PS-PS-PS vs PS-FS-PS	0.277	**0.036**	0.183	0.191	**0.006**	0.827	0.390
PS-PS-PS vs FS-PS-FS	**<0.001**	**<0.001**	0.102	**0.016**	**0.040**	**0.008**	0.124
PS-FS-PS vs FS-FS-FS	**0.008**	0.206	0.266	0.623	0.216	**0.008**	0.258
PS-FS-PS vs FS-PS-FS	**0.004**	0.093	0.753	0.250	0.470	**0.005**	0.491
FS-PS-FS vs FS-FS-FS	0.431	0.669	0.422	0.507	0.602	0.843	0.656
Season	**0.008**	0.173	0.119	**0.002**	**0.007**	**0.033**	**<0.001**
Linear change season	**0.003**	0.073	0.165	**0.026**	0.105	**0.016**	**0.001**
Seed lot	**<0.001**	0.160	0.511	**0.015**	0.098	**<0.001**	**<0.001**
Selection treatment × Season	**0.005**	0.427	0.799	0.759	0.212	0.255	0.914
PS-PS-PS vs FS-FS-FS × Linear Season	0.616	0.960	0.728	0.332	0.220	0.954	0.694
PS-PS-PS vs PS-FS-PS × Linear Season	0.052	0.817	0.611	0.648	0.321	0.153	0.921
PS-PS-PS vs FS-PS-FS × Linear Season	0.104	0.776	0.623	0.362	0.295	0.148	0.601
PS-FS-PS vs FS-FS-FS × Linear Season	0.143	0.856	0.872	0.606	0.812	0.138	0.769
PS-FS-PS vs FS-PS-FS × Linear Season	0.738	0.958	0.319	0.648	0.955	0.986	0.672
FS-PS-FS vs FS-FS-FS × Linear Season	0.255	0.814	0.402	0.953	0.856	0.133	0.869
Selection treatment × Seed lot	**<0.001**	0.990	0.803	0.552	0.350	**<0.001**	0.636
PS-PS-PS vs FS-FS-FS × Seed lot	**<0.001**	0.858	0.767	0.694	0.622	**0.018**	0.600
PS-PS-PS vs PS-FS-PS × Seed lot	0.308	0.832	0.348	0.164	0.164	0.953	0.710
PS-PS-PS vs FS-PS-FS × Seed lot	**<0.001**	0.973	0.410	0.369	0.476	**0.001**	0.279
PS-FS-PS vs FS-FS-FS × Seed lot	**0.013**	0.942	0.640	0.378	0.308	**0.008**	0.976
PS-FS-PS vs FS-PS-FS × Seed lot	**<0.001**	0.770	0.985	0.577	0.104	**<0.001**	0.391
FS-PS-FS vs FS-FS-FS × Seed lot	0.125	0.860	0.735	0.839	0.818	0.600	0.320
Season × Seed lot	**<0.001**	0.615	0.057	0.763	0.122	**0.003**	0.628
Linear Season × Seed lot	**<0.001**	0.549	0.147	0.508	0.707	**0.001**	0.315
Selection treatment × Season × Seed lot	0.114	0.972	0.527	0.841	0.272	0.553	0.957
PS-PS-PS vs FS-FS-FS × Linear Season × Seed lot	0.763	0.978	0.491	0.691	0.766	0.606	0.620
PS-PS-PS vs PS-FS-PS × Linear Season × Seed lot	0.377	0.996	0.228	0.369	0.913	0.592	0.712
PS-PS-PS vs FS-PS-FS × Linear Season × Seed lot	0.383	0.735	0.330	0.305	0.499	0.409	0.469
PS-FS-PS vs FS-FS-FS × Linear Season × Seed lot	0.497	0.972	0.785	0.282	0.945	0.382	0.788
PS-FS-PS vs FS-PS-FS × Linear Season × Seed lot	0.678	0.759	0.581	0.802	0.437	0.636	0.852
FS-PS-FS vs FS-FS-FS × Linear Season × Seed lot	0.274	0.820	0.458	0.403	0.289	0.108	0.887

3.4). For PLRV in Experiment 2, a significant two-way interaction between selection treatment and season (Table 3.3) showed that the difference in virus incidence between FS-FS-FS and PS-PS-PS increased with season.

PVY and PVA were generally present at low levels (Figure 3.5, Table 3.4) and the decrease in virus incidence by applying positive selection compared to farmers' selection was not significant.

The decrease by applying positive selection was also not significant for the incidence of PVS in Experiments 1 and 2, with highly infected seed lots of cv. Victoria, and PVM in both cultivars in Experiments 1, 2 and 3 (Figure 3.5, Tables 3.3 and 3.4). For PVS in Experiment 3, significant selection treatment × seed lot interaction (Table 3.3) showed that in the farm-saved seed lot of cv. Rwangume with intermediate infection levels by PVS, PS-PS-PS resulted in lower incidence of PVS than FS-FS-FS whereas in the other, highly infected seed lots of cv. Victoria there was no decrease in PVS incidence by positive selection (Figure 3.5).

3.3.2. Differences in virus incidence between seed lots

In all experiments there was a significant effect of the seed lot on the percentage clean plants (Table 3.3). All seed lots of cv. Victoria (5G, 4G or market seed) showed (almost) no clean plants (Figure 3.4). The level was significantly lower than that of the 3G seed lots of cv. Katchpot 1 in Experiments 1 and 2 and that of the 5G farm-saved seed lot of cv. Rwangume in the later seasons in Experiment 3 (Figure 3.5).

PLRV and PVX were present at intermediate levels in all seed lots in all experiments. There were no effects of the seed lot on PLRV incidence in Experiments 1 and 3 (Table 3.3), whereas in Experiment 2, the 3G seed lot of cv. Victoria had a higher PLRV incidence than the 3G seed lot of cv. Katchpot 1 (Figure 3.5). PVX incidence was significantly higher in the 3G seed lot of cv. Victoria than in that of cv. Katchpot 1 in Experiments 1 and 2; it was not affected by the seed lot in Experiment 3 (Table 3.3). No significant interactions between seed lot and other experimental factors were found for incidence of these viruses.

In general, a low incidence of PVY and PVA was found in Experiments 1 and 2 (Figure 3.5) and there were no significant effects of seed lot on the incidence of PVY and PVA in these experiments (Table 3.3). In Experiment 3, effects of seed lot were significant for PVY (Table 3.3), with higher incidences in the 4G and market seed lots of cv. Victoria than in the 5G farm-saved seed of cv. Rwangume (Figure 3.5); no significant effects of seed lot on PVA incidence were found in Experiment 3 (Table 3.3). Regarding PVY and PVA incidence, there were no significant interactions between the experimental factors in the experiments.

In seed lots from cv. Victoria, PVS and PVM incidences were very high in all seasons at (almost) 100% in all experiments, whereas seed lots from cv. Katchpot 1 (in Experiments 1 and 2) and cv. Rwangume (in Experiment 3) had significantly lower incidences of PVS and PVM (Figure 3.5). Significant linear season × seed lot interaction showed that in Experiment 1 the difference between seed lots in PVS incidence tended to become smaller with season. Significant seed lot × selection treatment and seed lot × season interactions

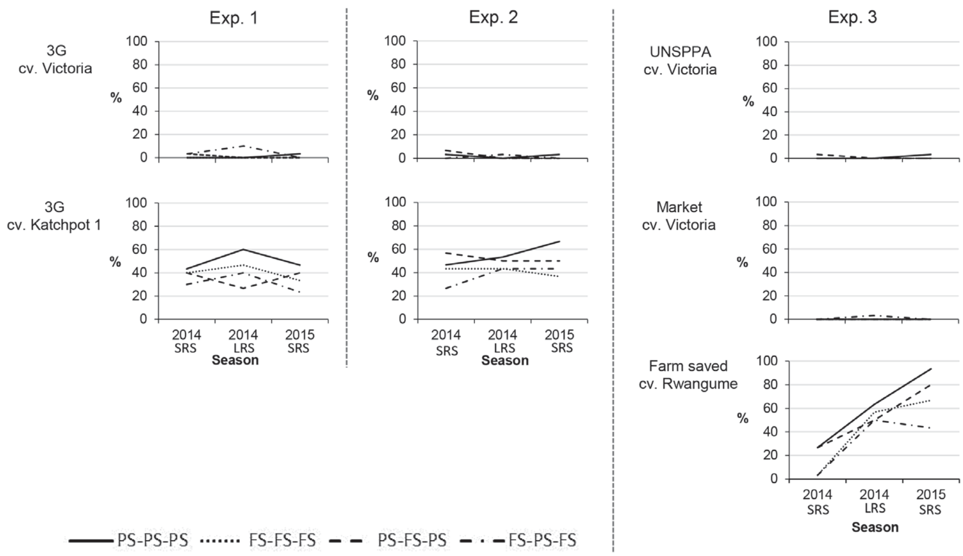


Figure 3.4. Clean plants (%) found at emergence in Seasons 2014-SRS, 2014-LRS and 2015-SRS as affected by different seed selection treatments in the previous seasons in different seed lots in the three experiments

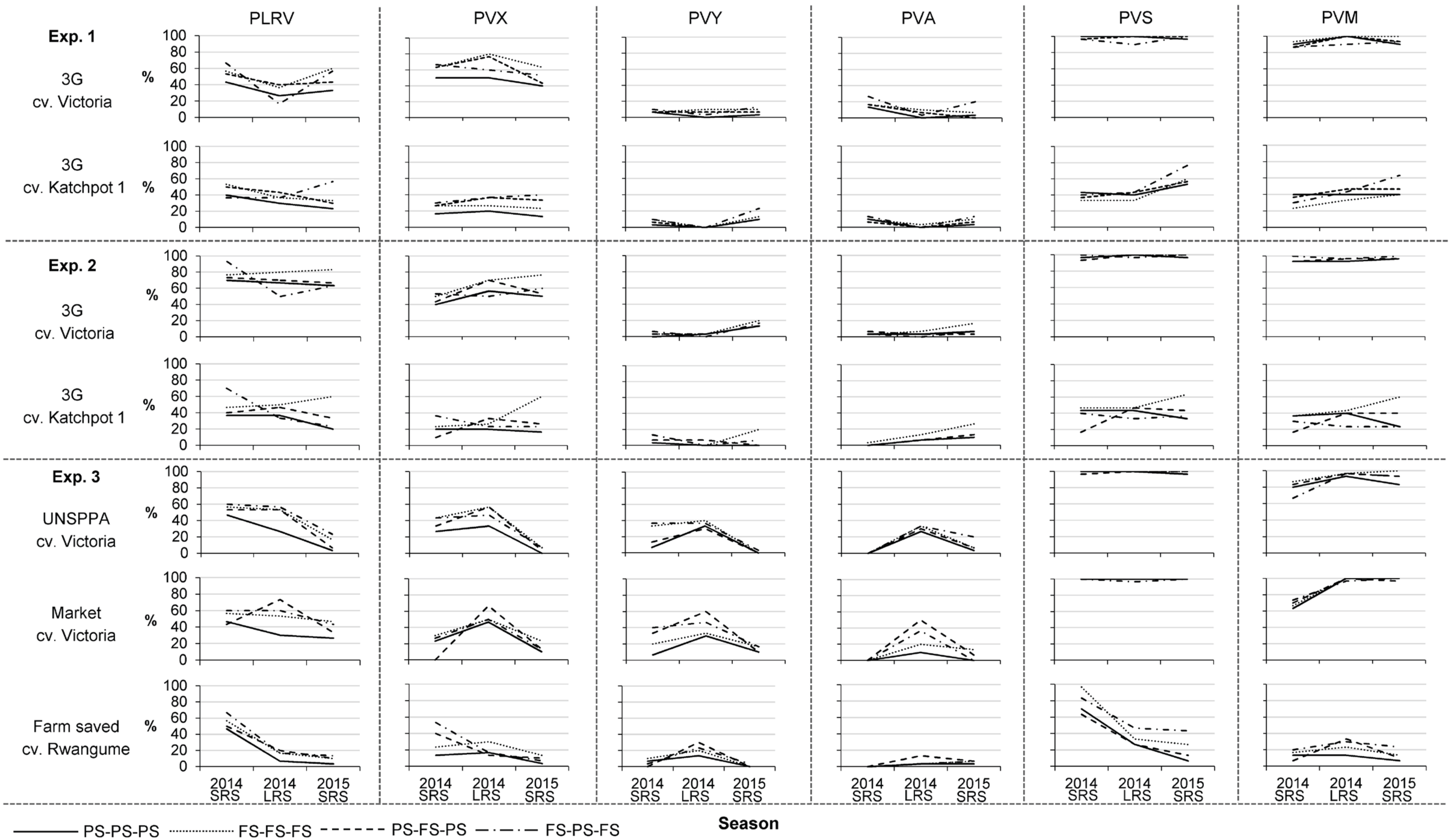


Figure 3.5. Virus incidence (% of infected plants) found at emergence in Seasons 2014-SRS, 2014-LRS and 2015-SRS as affected by the different seed selection treatments in the previous seasons in different seed lots in the three experiments

in Experiment 3 showed that the difference between seed lots in PVS incidence was larger under PS-PS-PS than under FS-FS-FS treatment, and that differences in incidence between seed lots increased with season (Table 3.3, Figure 3.5). In Experiments 1 and 2, a significant seed lot × selection treatment interaction was found for PVM incidence.

3.3.3. Changes in virus incidence over time

Because different selection methods were thought to exert their effects season after season, with the difference between them becoming gradually larger with time, it was expected that there would be significant interactions between season and selection treatment, especially between season and the contrast between continuously positive selection and continuously farmers' selection.

There were no significant changes across the seasons in percentage of clean plants in Experiments 1 and 2, nor any significant interactions between seed lot and season or the contrast between PS-PS-PS and FS-FS-FS and season (Table 3.3); this shows that the percentage of clean plants did not change differently in time between the seed lots or between the most extreme selection treatments. Only incidental interaction between season and the contrast between continuous positive selection and the treatment in which positive selection was interrupted by one season of farmers' selection were found in Experiment 2.

The virus incidence often fluctuated strongly over seasons for viruses present at intermediate levels, like PLRV and PVX in all seed lots and PVY and PVA in the seed lots of Experiment 3 (Figure 3.5). There was limited fluctuation in time for viruses present at (almost) 100% incidence, like PVS and PVM in seed lots of cv. Victoria, or present at very low levels, like PVY and PVA in Experiments 1 and 2 (Figure 3.5).

For PLRV and PVX, present at intermediate levels in all experiments, the virus incidence usually fluctuated strongly over seasons (Figure 3.5), whereas main effects of season were not significant. In Experiment 2, significant interactions between season and selection treatment (for PLRV) and between season and the contrast between continuously FS and continuously PS (for PVX) showed that the difference between FS-FS-FS and PS-PS-PS in incidence of these viruses significantly increased with time (Table

Table 3.4. Effect of different selection treatments on the virus incidence in the experiments across seed lots and seasons 2014-SRS, 2014-LRS and 2015-SRS and the change in incidence of treatments including positive selection compared to farmers' selection only (in parentheses angular transformed data of the proportions)

		Experiment 1			Experiment 2			Experiment 3		
Virus	Treatment	Incidence %	Change in incidence %	Relative change %	Incidence %	Change in incidence %	Relative change %	Incidence %	Change in incidence %	Relative change %
Clean	PS-PS-PS	26 (24.0 a)	+6	+28	29 (26.3 a)	+8	+37	21 (18.5 a)	+7	+47
	PS-FS-PS	18 (19.2 a)	-2	-8	27 (25.2 ab)	+6	+29	18 (16.7 a)	+4	+26
	FS-PS-FS	18 (20.7 a)	-2	-11	19 (19.7 bc)	-2	-8	11 (10.9 b)	-3	- 21
	FS-FS-FS	20 (18.5 a)			21 (20.7 bc)			14 (12.2 b)		
	$LSD_{0.05}$	6.27			4.77			3.25		
PLRV	PS-PS-PS	33 (32.7 a)	-13	-29	49 (44.3 a)	-17	-26	26 (26.5 a)	-14	-35
	PS-FS-PS	43 (40.7 ab)	-3	-6	55 (49.0 a)	-11	-16	38 (34.8 b)	-3	-6
	FS-PS-FS	45 (42.8 b)	-1	-2	56 (50.4 a)	-10	-15	44 (41.5 b)	+4	+9
	FS-FS-FS	46 (43.7 b)			66 (57.3 b)			41 (39.8 b)		
	$LSD_{0.05}$	10.23			6.05			7.79		
PVX	PS-PS-PS	32 (32.3 a)	-16	-33	34 (35.6 a)	-17	-34	19 (20.2 a)	-12	-7
	PS-FS-PS	47 (43.2 b)	0	0	39 (37.6 a)	-12	-23	26 (25.9 ab)	-5	-14
	FS-PS-FS	48 (43.9 b)	+1	+1	41 (38.1 a)	-10	-20	29 (27.3 ab)	-2	-5
	FS-FS-FS	47 (43.6 b)			51 (46.5 b)			31 (30.7 b)		
	$LSD_{0.05}$	8.27			6.39			8.47		
PVY	PS-PS-PS	4 (6.6 a)	-4	-53	3 (4.9 a)	-5	-60	12 (14.5 a)	-7	-38
	PS-FS-PS	6 (9.9 a)	-2	-27	6 (7.8 a)	-2	-33	19 (19.7 ab)	0	0
	FS-PS-FS	10 (13.6 a)	+2	+20	7 (10.3 a)	-1	-13	23 (24.3 b)	+4	+21
	FS-FS-FS	8 (13.3 a)			8 (8.7 a)			19 (21.6 a)		
	$LSD_{0.05}$	6.71			7.24			7.89		
PVA	PS-PS-PS	5 (8.1 a)	-4	-47	5 (8.1 a)	-7	-57	5 (7.0 a)	-4	-44
	PS-FS-PS	6 (9.5 ab)	-3	-35	6 (9.7 a)	-6	-52	12 (13.8 b)	+3	+36
	FS-PS-FS	13 (16.8 b)	+4	+35	4 (7.0 a)	-8	-61	11 (12.0 b)	+2	+20
	FS-FS-FS	9 (14.5 ab)			12 (14.0 a)			9 (10.8 ab)		
	$LSD_{0.05}$	6.34			6.90			4.82		
PVS	PS-PS-PS	72 (65.1 a)	+1	+2	69 (62.4 ab)	-7	-9	78 (70.5 a)	- 6	-7
	PS-FS-PS	72 (65.1 a)	+1	+2	67 (60.9 ab)	-9	-12	78 (70.0 a)	- 6	-7
	FS-PS-FS	74 (64.7 a)	+3	+5	68 (58.6 a)	-8	-10	86 (76.5 b)	+2	+2
	FS-FS-FS	71 (65.0 a)			76 (67.1 b)			84 (76.0 b)		
	$LSD_{0.05}$	5.85			6.25			4.39		
PVM	PS-PS-PS	67 (60.1 a)	-2	-3	64 (57.4 a)	-7	-9	61 (54.3 a)	-6	-8
	PS-FS-PS	68 (60.5 a)	+3	+5	64 (57.9 a)	-7	-9	66 (57.3 a)	-1	-2
	FS-PS-FS	68 (59.7 a)	+3	+5	62 (58.9 a)	-8	-11	67 (59.8 a)	0	0
	FS-FS-FS	65 (60.0 a)			70 (61.4 a)			67 (61.3 a)		
	$LSD_{0.05}$	5.94			6.28			7.01		

Different *letters* indicate significant difference between means according to LSD test at 5% level
PS=Positive Selection
FS=Farmers' Selection

3.3); the lowest PLRV incidence was found when PS-PS-PS was applied. In Experiment 3, PLRV and PVX incidence tended to decrease significantly with time in cv. Victoria/UNSPPA and cv. Rwangume (Figure 3.5).

In Experiments 1 and 2, no or a low incidence of PVY and PVA was found. A weak linear increase across the seasons was present for PVA in Experiment 1, but no further season-related effects were observed for PVY or PVA in these experiments (Figure 3.5, Table 3.3). In Experiment 3, the incidence in PVY and PVA fluctuated across seasons. None of the changes in PVY and PVA incidence across season was related to the selection treatments affecting these changes, as shown by the lack of selection treatment × season interactions (Table 3.3).

In seed lots from cv. Victoria, PVS and PVM were present in all seasons at (almost) 100% incidence in all experiments, whereas the seed lots from cv. Katchpot 1 in Experiments 1 and 2 and from cv. Rwangume in Experiment 3 had lower incidences of PVS and PVM (Figure 3.5). In Experiment 1, the difference in PVS incidence between seed lots tended to decrease linearly with time as shown by a significant interaction between the linear components of seed lot and season (Table 3.3); this was found because, while cv. Victoria remained almost fully infected in time, the infection levels in cv. Katchpot 1 increased in time. No significant effects of season or interactions between seed lot and season were found in Experiment 2. In Experiment 3, again the interaction between seed lot and the linear component of season was significant. Also in Experiment 3, the two seed lots from cv. Victoria remained fully infected in time, but in contrast to Experiment 1, the PVS incidence in the third seed lot, now the 5G farm-saved seed lot of cv. Rwangume in which a very high incidence was present in the 2nd season (SRS- 2014), declined efficiently in the subsequent seasons (Figure 3.5, Table 3.3). In none of the experiments, the seed lot specific decrease or increase in PVS incidence in time was driven by the selection treatments, because there were no significant three-way interactions. For PVM incidence, there were no effects of season in Experiment 1, whereas small linear changes in time were found in Experiments 2 and 3. In Experiment 2, there was a decrease over time in cv. Katchpot 1. In Experiment 3, across the seasons there was a significant increase in PVM incidence. No interactions with season were significant for PVM incidence.

3.3.4. Aphid monitoring

Aphid catches varied among the three locations and among seasons (Figure 3.2). The highest records of aphids were found in Karengyere, the location of Experiment 1, in the short rainy seasons 2014-SRS, with a total number of 2121, and 2015-SRS, with a total number of 3096. In the long rainy season 2014-LRS, a total number of 385 was counted. In Kachwekano, the location of Experiment 2, the total number was 557 in the 2nd season, 2014-SRS, and 303 in the 4th season, 2015-SRS, while in the 3rd season, 2014-LRS, a total number of 226 was recorded. The 3rd season 2014-LRS was characterised by little rainfall throughout the growing period; in the 1st season 2013-LRS and 3rd season 2014-LRS rainfall was more spread throughout the season than in 2014-SRS and 2015-SRS (Figure 3.3). In Experiment 3, the lowest total number of the aphid catches was found with 265 in the 2nd season 2014-SRS, and 140 in the 4th season 2015-SRS; in the 3rd season 2014-SRS 84 aphids were caught. At all three sites aphid flights were prevalent before and during the recommended period for positive selection.

3.3.5. Virus incidence in crops from the starting seed lots

Due to technical inability in setting up a local virus testing facility, the virus incidence in the starting seed lots in the first season could not be assessed immediately after emergence as in later seasons, but only at the moment of positive selection, i.e. just before full flowering. In the crops grown from the 3G seed lots in the first season in Experiment 1 (Table 3.2), 5% of the plants of cv. Victoria and 75% of the plants of cv. Katchpot 1 were fully free of virus at that moment (Table 3.2). In cv. Victoria, considerable incidence of PLRV and PVX was found (20 and 23% of the plants, respectively), a low level of PVY (5%), no PVA and high levels of PVS and PVM (95% and 63%, respectively). In the crop from cv. Katchpot 1, the incidences of PLRV and PVX were low (3 and 7%, respectively), and for PVY and PVA incidental (each 2%). In crops from the seed lot of this cultivar, a PVS incidence of 17% and a PVM incidence of 25% were found.

In Experiment 3, there were no fully virus-free plants in the crops from the 4G UNSPPA and local market seed lots of cv. Victoria, but notably 47%

virus free plants in the crop from the 5G farm-saved seed of cv. Rwangume. All three crops showed minor infections with PLRV (2%, 8%, and 7% respectively) and (minor) infections with PVX (UNSPPA 5%, local market 3%, farm-saved seed 18%). Incidence of PVY was absent in the seed lot from UNSPPA, and low in the market and farm-saved seed lots (2%); PVA was found to a minor extent in all three seed lots (5%, 7% and 7%, respectively). Also in this experiment crops from the cv. Victoria seed lots (from UNSPPA and the local market) showed high infection with PVS (100%), and PVM (65% and 78%, respectively); in plants from the farm-saved seed lot of cv. Rwangume these viruses were also present but at a much lower level (PVS 32%, PVM 12%).

3.3.6. Efficiency of plant selection regarding virus incidence in the first season

Comparing the virus incidences in the full plots from the original seed lots to those in the PS plants selected in the first season (Table 3.2) revealed that PS reduced the incidence of PLRV and PVX in the plants to be used for seed production to low levels in cv. Victoria and to no infection in cv. Katchpot 1 in Experiment 1 (Table 3.2), but the effects were hardly significant (*P*=0.051, Table 3.2). For PVY and PVA, where virus levels were already lower than those of PLRV and PVX, the reduction in virus incidence by selecting PS plants was not significant. There were also no significant differences between incidence levels in plants from the original seed lot and PS selected plants for the other viruses (PVS and PVM) in Experiment 1, nor for any of the viruses in Experiment 3 (Table 3.2).

We noticed there were large differences in the fraction of plants with PLRV and PVX between replicated plots in both experiments, with some plots being fully clean and others infected to a considerable extent. In Experiment 1, the blocks were laid out in a linear outline starting from Block I to Block III. In Block III and especially in the last plots, incidences of PLRV were highest, probably because these plots were closest to the border of the field with bushes. Also, PVX incidences were most abundant in the last plots. In Experiment 3, most incidences of PLRV and PVX were found in the outer plots of the blocks.

3.3.7. Increase in virus incidence after plant selection

The quality of the tubers produced after a season of selection was assessed in plants soon after emergence in the next season; the early time was necessary to avoid possible early primary infections interfering with the assessment. In the second season (2014-SRS), tuber data at emergence could be compared with the data taken of the plants they originated from at the moment when positive selection took place (2013-LRS). Regardless of the selection treatment, the virus incidence in the plants from these tubers was considerably higher than the incidence found in the plants they originated from at the moment before full flowering (i.e. the moment at which also positive selection took place), whereas the percentage of clean plants (when present) was lower (Table 3.2). This suggests the infection levels increased in the period between selecting plants and planting in both selection treatments.

3.4. Discussion

3.4.1. Reduction of virus incidence by positive selection as compared to farmers' selection

Our results clearly show that crops planted with seeds from positive selection have a reduced virus incidence compared to those from farmers' selection when the treatments are applied over multiple (in our case: three) seasons, thereby reducing the level of secondary infection in the next-season crop (Tables 3.3 and 3.4; Figures 3.4 and 3.5). Selection treatments in which positive selection was applied in one or two out of the three seasons took an intermediate position. However, this reduction of virus incidence by positive selection i) was not found for all virus species; and ii) the reduction was less strong than expected based on Gildemacher et al. (2011) and Schulte-Geldermann et al. (2012).

Positive selection for different virus species. The reduction in virus incidence by positive selection was clear for PLRV and PVX in all seed lots. These virus species display clear visual symptoms (Loebenstein et al., 2001) and were present at intermediate incidence (Figure 3.5). Incidences of PVY and

PVA (displaying mild visual symptoms) could be maintained at the levels as assessed after emergence in the 2nd season, despite a small (not significant) trend to increase at the end in Experiment 2 in Kachwekano. Symptoms for PVS and PVM are poorly visible in the crop (Loebenstein et al., 2001). The initial high percentage of incidence for PVS and PVM in cv. Victoria also explains why positive selection was not able to significantly increase the percentage of clean plants in seed lots from this cultivar (Table 3.3 and 3.4). The levels of PVS and PVM in cv. Katchpot could reasonably be maintained across years by positive selection, especially in Experiment 2. In cv. Rwangume in Experiment 3, a decrease in PVS incidence was found across seasons (Figure 3.5), but this was not exclusively found under PS-PS-PS management. Cv. Rwangume might be resistant to PVS and may be able to combat the virus itself. However, important may be incomplete autoinfection of tubers (Bertschinger et al. 2017). Incomplete autoinfection will result in planting partly clean seed because not all daughter tubers of an infected plant will be infected. A regeneration (meaning more clean plants) of a degenerated crop might be enhanced by applying positive selection in cv. Rwangume, because of a higher percentage of cleaner plants. In all other seed lots a regeneration by applying positive selection was possible for selected viruses present at intermediate incidence levels, like PLRV and PVX. The clear significant effect of the seed lots, which was attributed to the different cultivars tested in the experiments, is in line with the results of Schulte-Geldermann et al. (2012) that cultivars or genotypes differ in their response to the tested viruses.

Reasons for limited gain by positive selection. There are several possible reasons why positive selection did not reduce the virus level as strongly as we expected in advance.

An important factor for the limited gain by positive selection may be a high (risk for) primary infection in this region, because of (i) a high basic level of virus incidence in the environment, as shown by Fuglie (2007), and even the 3G seed lots having a high incidence of PVS and PVM (Figure 3.5, Table 3.2) and (ii) a high risk of virus transmission. The high risk of virus transmission in our experiments can be shown by (1) the seasonal fluctuations in all selection treatments that indicate reinfection occurred (Figure 3.5) and (2) the increase in virus incidence after the moment of selecting in the first season (Table 3.2). A high risk of virus transmission in the region might be caused by (a) the presence of aphids already before and after the moments of positive selection (Figure 3.2), (b) field traffic including manual spraying, and (c) the relatively small plot size (Pourrahim et al. 2007). The average area of potato plots in Kabale and Kisoro districts was shown to be 0.23 ha (Kaguongo et al. 2008). In our experiments, the small experimental plots and the presence of farmers' selection plots will have aggravated this risk for primary infection. For mechanical spread of viruses the movement of the sprayer through the field (to spray against *Phytophthora infestans*) or walking through the potato plots to select the plants might have enhanced virus spread, particularly for PVX. Different aphid pressure throughout the seasons (Figure 3.2) and different locations including neighbouring crops (Table 3.1) may determine infection pressure through the presence and abundance of aphid transmitted virus diseases (e.g., PLRV) (Figure 3.2). Windy and open environments do not favour aphid pressure, which might be the reason for the low number of aphids in Experiment 3.

Another reason for achieving less reduction in virus incidence by positive selection than expected (Figure 3.5) and a lower number of clean plants (Figure 3.4) will have been the low selection pressure possible in the plots. Bacterial wilt (*Ralstonia solanacearum*) was common in many fields limiting the number of plants available for positive selection. Moreover, a minimum number of seed tubers was needed to plant the field experiments for the next season; therefore, it was necessary to choose and select 37.5% of the plants in the net plot. At the yield levels in Uganda this is a realistic proportion for a farmer's field in order to have enough medium-sized seed tubers for the same area of land in the next season, due to low multiplication rate of the plants. Besides, it turned out to be very difficult to find fully vigorous plants, which might be attributed to the growing conditions in this region, such as poor soil fertility and poor rainfall which reduce plant vigour as well.

3.4.2. Seed tuber quality of the starting seed lots

The seed tuber quality of the starting seed lots (as assessed in crops from these tubers at the moment of flowering) of the different sources and cultivars varied but was not always as expected. The quality declared 3G and 4G seed of the research station KAZARDI and the private seed grower UNSPPA, respectively, was expected to be clean or contain little virus, but this was not the case. Of the 3G plants 5-75% were clean, whereas no clean plant was found in the crop from the 4G UNSPPA seed lot (Table 3.2). Incidence of PVS and PVM was already high in (crops from) these tubers, particularly for cv. Victoria. Cv. Victoria may be more susceptible for PVS and PVM infection than cv. Katchpot 1, of which the original 3G seed had the lowest virus incidence of all seed lots, with 75% clean plants. The high incidence of these viruses suggests that PVS and PVM are not reliably selected against in the seed system sector. PVS and PVM also showed high incidence in the seed lot from the local market and to some extent in the farm-saved seed lot in Experiment 3.

Recycled seed potatoes from the informal sector like the market seed were expected to have the highest virus incidence, but surprisingly low levels of PLRV, PVX, PVY and PVA were found. This also held for the farm-saved 5G seed of cv. Rwangume; it was with almost 50% of clean plants healthier than expected.

3.4.3. Efficiency of plant selection

In the first season the virus incidence in the positive-selected plants was assessed at the moment of positive selection and compared to that in the unselected FS crops (Table 3.2). Although virus infection levels were generally lower or even zero in the positive selection plants, this turned out to be not or hardly statistically significant (P=0.051 for PLRV and PVX in Experiment 1). This lack of significance was at least partly due to infections being localised, resulting in an uneven distribution of the virus in the blocks and plots, which greatly increased variation.

3.4.4. Recommendations

Positive selection is selecting plants based on visual symptoms, which is relevant for innovative seed system management practices in low-income countries. The research showed that positive selection can be a long-term strategy to keep virus incidence with clear visual symptoms in plants at lower levels than in farmers' selection. However, it is hard to flush out viruses where no obvious symptoms occur or when seed lots are fully infected: therefore, positive selection also has limitations. Another overall solution to combat degeneration is to use virus-free and virus-resistant planting material from institutes and private seed growers, which currently might be difficult to purchase in Uganda. Therefore, institutes and private seed growers should invest in more reliable virus testing and seed production management. However, due to financial constraints of smallholder farmers this cannot be seen as a silver bullet for Uganda (Thomas-Sharma et al., 2016). Another recommendation for farmers might be the seed plot technology (Kakuhenzire et al., 2005; Kinyua et al., 2015), where a separate plot of tubers is grown for production of seed tubers. Within this plot, positive selection is applied and tubers from the selected plants are used to establish the next-season seed plot, whereas the remaining tubers are used to grow the ware crop. Positive selection as an innovative seed degeneration management method for resource poor farmers is currently the best-to-fit and a resilient method; this suggests farmers have to be trained in good seed management practices to achieve the best possible potato yields.

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CHAPTER 4

Potato yield and yield components as affected by positive selection during several generations of seed multiplication in southwestern Uganda

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Abstract

Potato (*Solanum tuberosum* L.) is an important crop in Uganda but production is low. There is no official seed system and farmers use potato tubers from a previous harvest as seed. This study investigated how effectively the seed technology positive selection enhanced yield and underlying crop characteristics across multiple seasons, compared to the farmers' selection method. Positive selection is selecting healthy plants during crop growth for harvesting seed potato tubers to be planted in the next season. Farmers' selection involves selection of seed tubers from the bulk of the ware potato harvest. Positive selection was compared to farmers' seed selection for up to three seasons in three field trials in different locations in southwestern Uganda using seed lots from different origins. Across all experiments, seasons and seed lots, yields were higher under positive selection than under farmers' selection. The average yield increase resulting from positive selection was 12%, but yield increases were variable, ranging from –5.7% to +36.9%, and in the individual experiments often not significant. These yield increases were due to higher yields per plant, and mostly higher weights per tuber, whereas the numbers of tubers per plant were not significantly different. Experimentation and yield assessment were hampered by a varying number of plants that could not be harvested because plants had to be rogued from the experimental plots because of bacterial wilt (more frequent under farmers' selection than under positive selection), plants disappeared from the experimental field and sometimes plants did not emergence. Nevertheless, adoption of positive selection should be encouraged due to a higher production and less virus infection of seed tubers in positive selected plants, resulting in a lower degeneration rate of potato seed tubers.

Keywords Multi-seasonal trials · Positive selection · Seed degeneration · Seed potatoes · Seed regeneration · Uganda · Yield increase

4.1. Introduction

Potato (*Solanum tuberosum* L.) is one of the main staple crops for food and nutrition security in Uganda (Whitney et al., 2017), where it serves also as a cash crop for smallholder farmers (Gildemacher et al., 2009; Olanya et al., 2012). While Uganda has a large potato production area, average yields with 4.2 Mg ha^{-1} are lower than in other East-African countries (FAO, 2019) and far below the attainable yield of 25 Mg ha^{-1} (International Potato Center, 2011). One of the most important yield-defining factors in potato production is the quality of the seed tubers planted (Struik and Wiersema, 1999; Haverkort and Struik, 2015). Smallholder farmers in Uganda generally plant tubers from an informal source, like their own harvest, the market or a neighbour (Gildemacher et al., 2009). Tubers for seed are mostly taken from the bulk of the ware potato harvest and selected based on size and visual inspection. This method is further referred to as 'farmers' selection' or FS. These successively cycled seed tubers are often highly degenerated due to accumulation of tuber-borne pests and diseases (especially viruses and bacteria), resulting in poor yield and poor quality of the harvest (Turkensteen, 1987; Salazar, 1996; Struik and Wiersema, 1999; Thomas-Sharma et al., 2016).

Due to the lack of a well-functioning formal seed system for purchasing high-quality and healthy seed tubers, Ugandan farmers have the following options to overcome poor seed quality. Farmers can buy quality-declared seed tubers from the Ugandan National Seed Potato Association (UNSPPA) (International Potato Center, 2011). However, the availability of these tubers often does not meet the high demand (CTA, 2014; Kakuhenzire et al., 2015). Moreover, many smallholder farmers cannot afford to buy these tubers. A promising option for improving seed tuber quality is the technique of positive selection whereby the most healthy-looking plants in a ware potato field are identified and pegged during flowering and checked for health thereafter. The tubers harvested from these most healthy-looking plants serve as seed tubers in the following growing season. With this technique the most healthy tubers are selected, a decrease in seed-borne pests and diseases can be realized and a possible increase in yield can be achieved (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012; Okeyo et al., 2018). Another option is using the seed plot technique[1], which seems appropriate for farmers who have a surplus of land to reserve it for improving their seed potatoes (Kakuhenzire et al., 2005; Kinyua et al., 2015).

Positive selection in ware crops was investigated earlier during one cropping cycle with an overall yield increase of 28% (Gildemacher et al., 2011), 30% (Schulte-Geldermann et al., 2012) and 37% (Siddique et al., 2017) compared to farmers' selection. Latest research in which positive selection was applied during multiple seasons (and thus for several generations of seed multiplication) confirmed the virus decrease (Priegnitz et al., 2019b) and yield increase (Okeyo et al., 2018). The objective of this study was to assess if positive selection during multiple seasons leads to an improvement in yield compared with farmers' selection and which yield components underlie this yield increase. Different sources of seed potatoes, potato cultivars, and locations were included in the study which was carried out in Kabale district, which is the most important potato cropping region of southwestern Uganda (Bonabana-Wabbi, 2013).

4.2. Material and methods

4.2.1. Experimental design and starting material

In Kabale district, the main potato production region of Uganda, three field experiments were conducted at three locations across four production seasons. The experiments had a split-plot design with three replicated blocks and with the seed potato lot as main factor and seed selection method as sub-factor. For the first two experiments, two high-quality 3G[2] seed tuber lots (cv. Victoria and cv. Katchpot 1) were purchased from the Kachwekano Zonal

[1] In the seed plot technology, a separate plot of tubers is grown by the farmer for production of seed tubers. Positive selection is applied within this plot and tubers from the selected plants are used to produce the next-season seed plot, while the remaining tubers are used to grow the ware crop.

[2] 3G seed (also called Basic Seed) refers to three generations of multiplying, starting from in-vitro culture and thereafter being multiplied in the greenhouse and in the field (International Potato Center, 2011). Currently, 3G seed can be purchased from the national research institute KAZARDI in Uganda. After 3G has another multiplication in the field it is called 4G. After 4G has another multiplication in the field it is called 5G.

Agricultural Research and Development Institute (KAZARDI). Both seed lots were planted in two locations: Karengyere (2433 m a.s.l.; Experiment 1) and Kabale (2246 m a.s.l.; Experiment 2); both sites belonged to the research station of KAZARDI. Experiment 3 was planted on fields of a local farm in Hamurwa (2220 m a.s.l.) using three seed lots: (1) 4G[2] seed tubers produced by the Ugandan National Seed Potato Production Association (UNSPPA), cv. Victoria; (2) seed tubers bought at the local market close to Kabale town (unknown generation), cv. Victoria; and (3) 5G[2] seed tubers from a local farm which saved seed tubers for own use, cv. Rwangume. More information on the locations is presented in Table 4.1. In all experiments, four seed selection treatments were applied: (1) positive selection (PS) in all seasons (referred to as PS-PS-PS), (2) alternating seed selection in the seasons starting with positive selection in the 1st season and followed by farmers' selection (referred to as PS-FS-PS), (3) alternating seed selection in the seasons starting with farmers' selection in the 1st season (referred to as FS-PS-FS), and (4) farmers' selection (FS) in all seasons (referred to as FS-FS-FS) (Figure 4.1). Per experimental plot, 60 tubers were planted in 6 rows at a spacing of 70 cm between rows and 30 cm within rows; for the net plot the border plants in the outer rows were excluded, so 40 plants were used for assessment. In the PS treatments, 15 healthy looking plants per plot were selected during crop growth and harvested separately; this accounts for plants from 37.5% of all seed tubers planted in the net plot. Seed tuber selection was done by farmers by selecting medium-sized seed tubers from these PS plants after storage at planting time. Under the local conditions, the harvest of 15 plants was needed to achieve enough medium-sized seed tubers for the next planting season. In the FS plots, plants were not selected during crop growth, but medium-sized seed tubers were selected by farmers at planting time from the stored tuber bulk of the former harvest. In a few cases in the 3rd and 4th season, there were not enough medium-sized seed potatoes and smaller-sized seed potatoes had to be planted in some plots (Table 4.2). For each of the four selection treatments, tubers from the replicated plots were combined before selecting the seed tubers.

Table 4.1. Information on the three experimental sites in Kabale district (adjusted from Priegnitz et al. (2019b))

	Experiment 1	Experiment 2	Experiment 3
Location	Karengyere	Kachwekano	Hamurwa
Elevation	2433 m asl	2246 m asl	2220 m asl
Longitude	29°47'57 E	29°56'5 E	29°54'56 E
Latitude	1°14'08 S	1°15'26 S	1°06'58 S
Soil	Ferralsols	Ferralsols	Ferralsols
Fertilisation	45 kg N/ ha	45 kg N/ ha	45 kg N/ ha
Seed spacing (between row × within row)	70 × 30 cm	70 × 30 cm	70 × 30 cm
Seed lots (seed source and cultivar)	3G KAZARDI/cv. Victoria 3G KAZARDI/cv. Katchpot 1	3G KAZARDI/cv. Victoria 3G KAZARDI/cv. Katchpot 1	4G UNSPPA/cv. Victoria Local market/cv. Victoria 5G Farm-saved/cv. Rwangume
Selection treatments	PS-PS-PS PS-FS-PS FS-PS-FS FS-FS-FS	PS-PS-PS PS-FS-PS FS-PS-FS FS-FS-FS	PS-PS-PS PS-FS-PS FS-PS-FS FS-FS-FS
Storage (all seasons)	DLS on wooden shelves	Wooden shed (dark) on wooden shelves	DLS on wooden shelves
Selection of seed tubers	Before planting	Before planting	Before planting
1st season: 2013- LRS			
Planting date	03.10.2013	04.10.2013	05.10.2013
Seed tuber size[a]	Medium	Medium	Medium
Average temperature in the growing period (°C)	Not available	18.8	Not available
Total rainfall in the growing period (mm)	83.5 (excl. 2013)	107.4	Not available
Flowering and PS pegging date 1st season	15.12.2013 (73 DAP[e])	15.12.2013 (72 DAP)	16.12.2013 (72 DAP)
Leaf sampling date 1st season	15.12.2013 (73 DAP)	-	16.12.2013 (72 DAP)
Haulm destruction date	21.01.2013 (110 DAP)	23.01.2013 (111 DAP)	21.01.2013 (108 DAP)
Harvest date	29.01.2014 (118 DAP)	30.01.2014 (118 DAP)	31.01.2014 (118 DAP)
Other cultural practices	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *Phytophthora infestans*) (4×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (6×)	Ploughing (2 ×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (4×)
Neighbouring crops	Potato, sorghum, wheat	Potato, sweet potato, beans	Sweet potato, beans, sorghum, maize, potato
2nd season: 2014- SRS			
Planting date	07.04.2014 (69 DAH)	06.04.2014 (67 DAH)	08.04.2014 (68 DAH)
Seed tuber size[a]	Medium	Medium	Medium
Average temperature in the growing period (°C)	Not available	18.5	Not available
Total rainfall in the growing period (mm)	183.6	61.2	Not available
Leaf sampling date	01.05.2014 (24 DAP)	01.05.2014 (25 DAP)	02.05.2014 (24 DAP)
Flowering and PS pegging date	12.06.2014 (65 DAP)	11.06.2014 (64 DAP)	12.06.2014 (64 DAP)
Haulm destruction date	17.07.2014 (100 DAP)	19.07.2014 (103 DAP)	21.07.2014 (103 DAP)
Harvest date	28.07.2014 (111 DAP)	29.07.2014 (113 DAP)	30.07.2014 (112 DAP)
Other cultural practices	Ploughing (2×) Weeding, incl. hilling up (2×) Spraying (against *P. infestans*) (3×)	Ploughing (2×) Weeding, incl. hilling up (2×) Spraying (against *P. infestans*) (3×)	Ploughing (2×) Weeding, incl. hilling up (2×) Spraying (against *P. infestans*) (4×)
Neighbouring crops	Potato, sorghum, wheat	Sweet potato, beans, sorghum, maize, potato	Beans, sorghum, maize, potato

3rd season: 2014- LRS			
Planting date	10.10.2014 (75 DAH)	09.10.2014 (73 DAH)	11.10.2014 (74 DAH)
Seed tuber size[a]	Cv. Victoria: medium Cv. Katchpot 1: small for one plot of PS-**FS**-PS, and FS-**PS**-FS, and mix of small and medium in PS-**PS**-PS, otherwise medium	Cv. Victoria: medium Cv. Katchpot 1: small size for one plot of PS-**PS**-PS, FS-**PS**-FS, FS-**FS**-FS, otherwise medium	4G UNSPPA/ cv. Victoria: small size for one plot of PS-**PS**-PS, and FS-**PS**-FS, otherwise medium Local market/ cv. Victoria: mix of small and medium in one plot of PS-**PS**-PS and FS-**PS**-FS, otherwise medium 5G Farm-saved seed/ cv. Rwangume: mix of small and medium in one plot of PS-**PS**-PS, small in one plot of PS-**PS**-PS and FS-**PS**-FS, otherwise medium
Average temperature in the growing period (°C)	Not available	18.6	Not available
Total rainfall in the growing period (mm)	250.4	197.5	Not available
Leaf sampling date	05.11.2014 (26 DAP)	05.11.2014 (27 DAP)	06.11.2014 (26 DAP)
Flowering and PS pegging date	18.12.2014 (69 DAP)	17.12.2014 (69 DAP)	18.12.2014 (68 DAP)
Haulm destruction date	28.01.2015 (110 DAP)	27.01.2015 (110 DAP)	26.01.2015(107 DAP)
Harvest date	03.02.2015 (116 DAP)	02.02.2015 (116 DAP)	04.02.2015 (116 DAP)
Other cultural practices	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (7×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (6×)	Ploughing (2 ×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (1×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (8×)
Neighbouring crops	Potato, peas, sorghum	Beans, sweet potato, potato	Sorghum, maize, beans, potato, sweet potato,
4th season: 2015-SRS			
Planting date	16.04.2015 (73 DAH)	14.04.2015 (72 DAH)	15.04.2015 (71 DAH)
Seed tuber size[a]	Cv. Victoria: small for one plot of PS-PS-**PS**, otherwise medium Cv. Katchpot 1: small for one plot of PS-FS-**PS**, otherwise medium	Cv. Victoria: small for one plot of PS-PS-**PS**, PS-FS-**PS**, and FS-FS-**FS** each, otherwise medium Cv. Katchpot 1: mix of small and medium in one plot of PS-PS-**PS**, small in one plot of PS-FS-**PS**, otherwise medium	Medium
Average temperature in the growing period (°C)	Not available	18.4	Not available
Total rainfall in the growing period (mm)	227.8	156.2	Not available
Leaf sampling date	14.05.2015 (28 DAP)	14.05.2015 (30 DAP)	15.05.2015 (30 DAP)
Flowering and PS pegging date	18.06.2015 (63 DAP)	17.06.2015 (64 DAP)	18.06.2015 (64 DAP)
Haulm destruction date	21.07.2015 (96 DAP)	23.07.2015 (100 DAP)	23.07.2015 (99 DAP)
Harvest date	04.08.2015 (110 DAP)	06.08.2015 (114 DAP)	07.08.2015 (114 DAP)
Other cultural practices	Ploughing (2×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (7×)	Ploughing (2×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (8×)	Ploughing (2×) Herbicide Glyphosate a.i. 360 g a.i./L (1×) Weeding, incl. hilling up (2×) Fungicide a.i. Mancozeb and a.i. Metalaxyl & Mancozeb (against *P. infestans*) (8×)
Neighbouring crops	Potato, sorghum	Sweet potato, beans, sorghum, potato	Sweet potato, beans, sorghum, maize

DAH Days after Harvest; *DAP* Days after Planting; *DLS* Diffuse Light Storage; *LRS* Long rainy season; *FS* Farmers' selection (see also Figure 4.1); *PS* Positive selection (see also Figure 4.1); *SRS* Short rainy season

[a] Medium size 30–60 mm, small size 5–30 mm; the selection treatment in **bold** refers to the planted seed

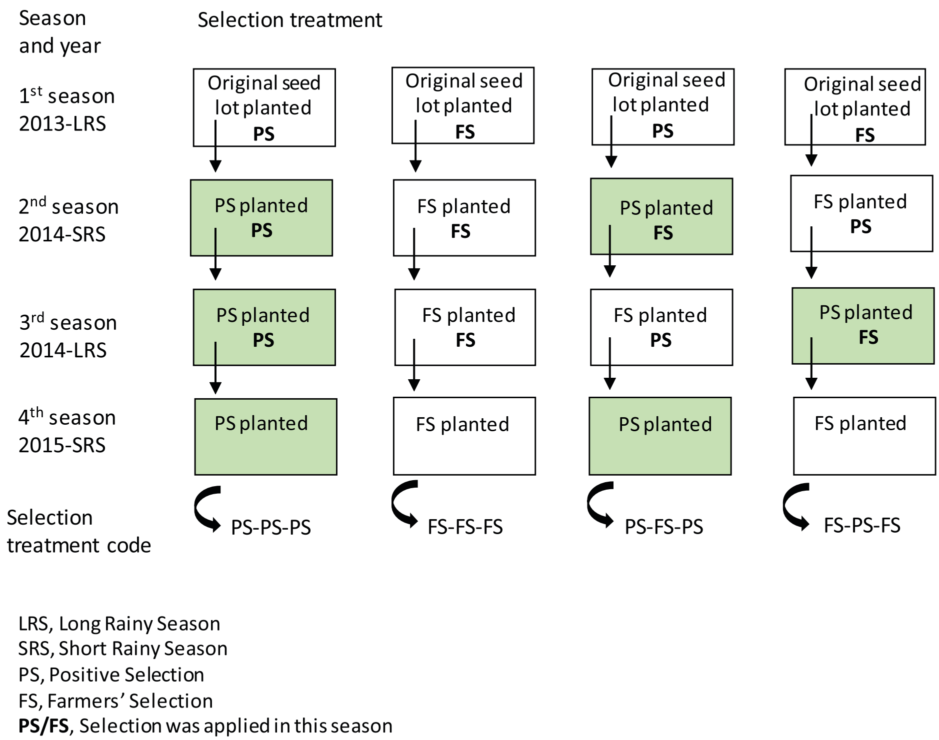

Figure 4.1. Scheme of selection treatments (in green when positive selection seed was planted) in the three experiments over the seasons (from Priegnitz et al., 2019b).

The southwestern region of Uganda is characterised by two rainy seasons in one calendar year, the Long Rainy Season (LRS; October–January), and the Short Rainy Season (SRS; February–June). Planting potatoes in both growing seasons was done because this is common practice in Kabale district (Gildemacher et al., 2009). The start of the experiments was in October 2013 (1^{st} season, LRS), when crops for seed tuber production were grown from the original seed lots and first plant selection took place; experiments continued with planting in subsequent seasons of April 2014 (2^{nd} season, SRS), October 2014 (3^{rd} season, LRS), and finally April 2015 (4^{th} season, SRS). Specific information of all experiments and locations is presented in Table 4.1. In the 4^{th} season, plants were selected according to treatment, but without replanting the produced tubers in a next season. Consequently, the selection treatment carried out in the 4^{th} season is not reflected in the experimental code because this treatment did not influence yield and underlying components of the crop in which it was carried out.

4.2.2. Haulm removal, tuber harvest and tuber storage

The haulm was manually removed between 96 and 111 days after planting (DAP) and tubers were harvested between 111 and 118 DAP (Table 4.1).
In the net plots receiving FS in a given season, tubers were harvested from all plants to determine tuber yield; in the plots receiving PS, tubers from the non-selected and the selected plants were harvested separately but the yields of the two fractions were summed to derive the yield per plot. During storage, the individual replicates of one treatment were combined and stored separately from the tubers of the other treatments.

Tubers were stored on wooden shelves either in a dark wooden shed (Experiment 2) or in a diffused light store (Experiments 1 and 3); the layer of tubers was sprinkled with insecticide a.i. Malathion 57% and covered with kikuyu grass (*Pennisetum clandestinum*) and couch grass (*Digitaria abyssinica*). Storage duration of the tubers until planting was between 69 and 75 days (Table 4.1).

4.2.3. Weather data

Weather data were derived from the internet platform awhere (awhere.com) for Experiment 2 (Figure 4.2); for Experiment 1 rain data were manually recorded at the KAZARDI station in Karengyere (Table 4.1). No reliable weather data were available for Experiment 3.

4.2.4. Measurement of agronomic characteristics

Plant numbers. The *number of emerged plants* in the net plot was recorded 35-36 DAP in the 1st season (2013-LRS), and during leaf sampling (24-30 DAP) in the 2nd, 3rd and 4th season (2014-SRS, 2014-LRS, 2015-SRS; Table 4.1). The purpose of leaf sampling was to check for virus infection of the seed tubers. Details on infection by individual viruses in those seed tubers can be found in Priegnitz et al. (2019b). Plant *establishment* (especially to

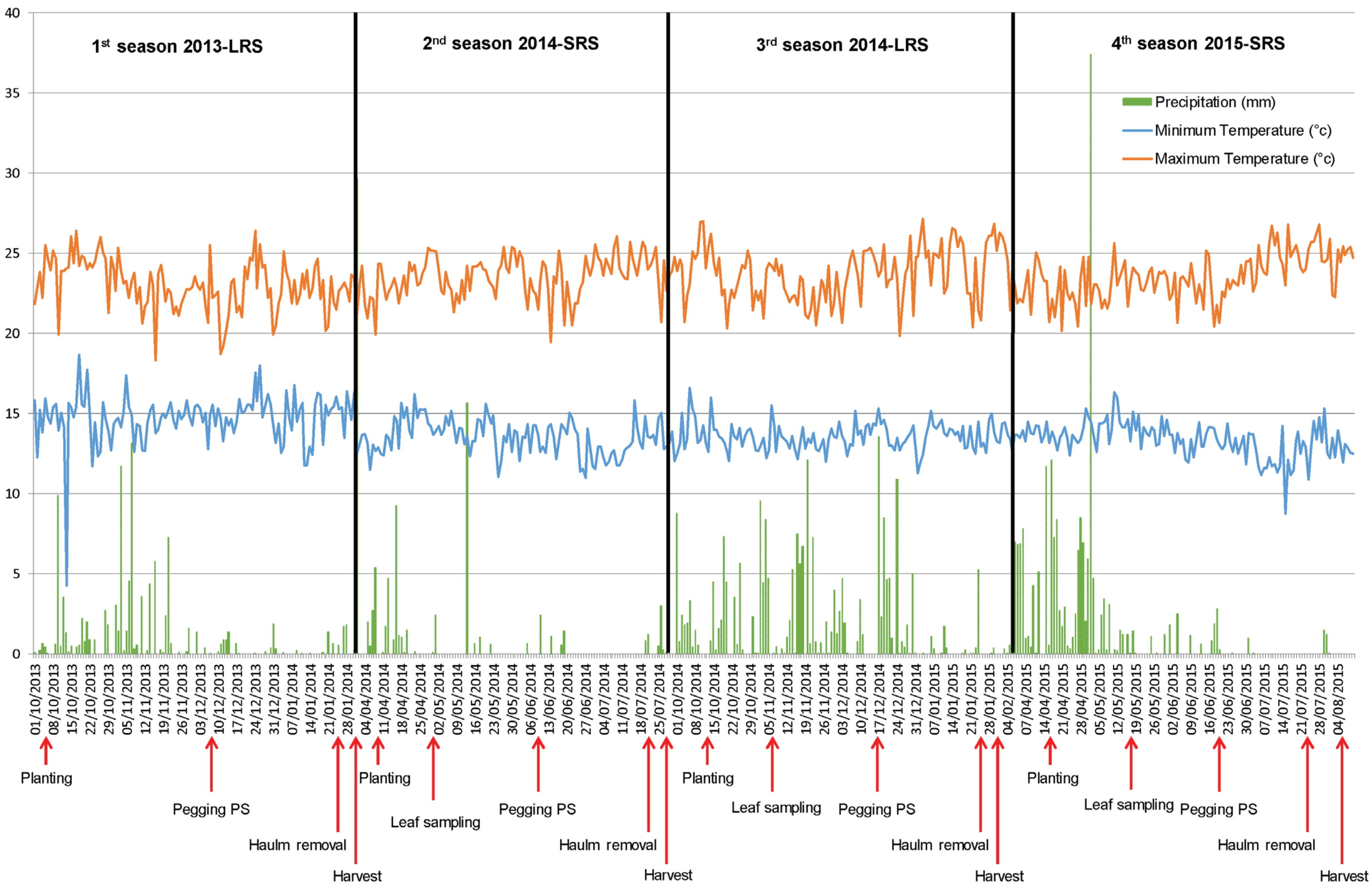

Figure 4.2. Weather data of Experiment 2 during the growing periods with important crop and experiment management practices (black lines indicate the next season). Data from Priegnitz et al. (2019b)

assess if no unaccounted loss appeared) was checked during PS pegging time (63 – 73 DAP). Plots were also inspected for bacterial wilt (*Ralstonia solanacearum*) every 10 days and, when infected, plants (including their tubers) were removed and their number was counted (*rogued plants*). At harvest, the *numbers of harvested plants* were recorded. In some cases, the number of plants at harvest was lower than the number of emerged plants minus the rogued plants, which might be attributed to thefts from the field. We defined these missing plants as "*unaccounted loss*". In Tables 4.2, 4.3, and 4.4 the numbers of *plants emerged, rogued, lost and harvested* are presented as the actual plant number and as percentage of the original number of seed tubers (planting positions) planted. In Table 4.5 and Figure 4.3, numbers of plants are presented as percentage.

Number of tubers, tuber yield, number of stems and ground cover. To establish number and yield of tubers resulting from the selection treatments in the previous year(s), data of all plants per net plot (including selected and non-selected plants in PS plots) were considered. At harvest, each plant was harvested separately and for each plant the total number of tubers was recorded. The average *number of tubers per harvested plant* in the net plot was derived from the sum of the individually harvested plants divided by the number of the harvested plants. The harvested *number of tubers per* m^2 was derived from the total number of tubers harvested per plot divided by the plot area. The *weight per* individual *tuber* was the total tuber fresh weight in the net plot divided by the total number of harvested tubers in the plot. The average *yield per plant* was calculated by dividing the total tuber fresh yield per plot by the number of harvested plants in the plot. The *total tuber fresh yield* was the total tuber fresh yield per plot recalculated into $Mg\ ha^{-1}$ from the planted area of the plot. Tubers of each plot were graded into *three size categories*: large (>60 mm), medium (30–60 mm), and small (5–30 mm) and the weight in each category was assessed.

Canopy development in all plots was measured as g*round cover* (%) every 10 days and estimated by using a wooden frame of 0.70 m × 0.90 m divided into 100 equal units (which equals 100%); if one unit was filled more than half with green foliage it was counted as one percentage. The values presented represent the maximum ground cover (Supplementary Material Table S4.2A – S4.4A). Main stems which emerged directly from the seed tuber were counted to assess *the number of stems* per plant.

Differences between selected and non-selected plants. Additionally, in all plots receiving positive selection in a given season (including the 4th season), the average yield per plant of the positive selected plants was calculated by dividing the total tuber fresh yield of the positive selected plants per plot by the number of the positive harvested plants in the plot, and the average yield per plant of the non-selected plants by dividing the yield of the non-selected plants in the plots receiving positive selection by the number of non-selected plants in these plots. To compare PS plants to non-selected plants in the same plot for number of tubers, the number of tubers of each harvested plant from positive selected plants and non-selected plants was assessed in all plots receiving the PS treatment.

4.2.5. Data analysis

Data were analysed using GenStat for Windows 18th Edition (VSN International 2016). General Analysis of Variance was used to test the effects of the factors selection treatment, seed lot and season and their interactions on the variables. The 1st season was not included in this ANOVA, because the seed planted in that season had not yet been subjected to different experimental selection treatments. Results of this 1st season are merely shown for comparison purposes. Where the *P*-value in the ANOVA indicated significant effects or interactions ($P < 0.05$), significances of differences between means were assessed by the Fisher's LSD test at $\alpha = 0.05$. Data related to proportions (numbers of plants emerged, rogued, unaccounted loss and harvested, and ground cover) were transformed before analysis. They were recalculated to proportions and angular transformations were applied (Fernandez, 1992). Proportions equal to 0 or 1 were replaced by (1/4n) and [1-(1/4n)] respectively, where n represents the total number of sampled plants or tubers per net plot (Fernandez, 1992).

To assess differences in tuber number per plant and yield per plant between positive selected plants and non-selected plants in the same plots, boxplots were generated using data from the PS plots in all four seasons. The number of tubers and yield per plant of positive selected plants and non-selected plants were compared and tested for significance with a paired *t*-test.

4.3. Results

For yield and its underlying components, the full outcome of the ANOVAs and the means for the individual treatments in the three experiments are shown in Tables 4.2 – 4.4; the supplementary data on yields per tuber size class, maximum ground cover and stem number per plant are shown in the Supplementary Material (Tables S4.2A – S4.4A). Significant three-way interactions (selection treatment × seed lot × season) were only found in Experiment 2 and only for the variates number of rogued plants, number of harvested plants (Table 4.3) and yield of large tubers (Supplementary Material Table S4.3A). There were some two-way interactions between selection treatment and seed lot and between selection treatment and season, whereas two-way interactions between seed lot and season were most often found (Tables 4.2 – 4.4, Supplementary Tables S4.2A – S4.4A). Table 4.5 presents the main effects of selection treatment and the interacting effects of selection treatment and seed lot, Figure 4.3 presents the main effect of season and the interacting effects of season and seed lot.

4.3.1. Effects of selection treatments

Fresh tuber yield per hectare. In Experiment 1, the selection treatment × seed lot interaction was significant. In cv. Victoria, the fresh tuber yield per ha was not significantly affected by the selection treatment, whereas in cv. Katchpot 1 the yield in the PS-FS-PS treatment was lower than the yield in the other treatments, which did not differ significantly from each other (Table 4.5). In Experiment 2, a significant main effect of selection treatment indicated that a lower yield was obtained in the FS-FS-FS treatment than in the other treatments, which did not differ significantly from each other (Table 4.3, Table 4.5). In Experiment 3, the average yield across the seed lots was highest in the PS-PS-PS treatment, but not significantly different from the other treatments (Table 4.4, Table 4.5).

Table 4.2. Effects of selection treatments, seasons and seed lots on agronomical characteristics in location Karengyere, Experiment 1 (selection treatment in bold refers to the seed planted in the specific season)

Treatment	Emergence		Rogued plants		Unaccounted plant loss		Harvested plants		Tubers per plant		Tubers per m^2		Weight per tuber (g)		Yield per plant (kg)		Tuber yield (Mg/ha)	
Relative change		%		%		%		%		%		%		%		%		%
2nd season: 2014- SRS																		
3G/cv. Victoria																		
PS-PS-PS	100.0 (120/120)	+2.5	0.0 (0/120)	-	2.5 (3/120)	-1.6	97.5 (117/120)	+0.8	6.2	+10.7	28.9	+14.2	49.0	-8.1	0.304	+4.8	14.2	+7.5
PS-FS-PS	97.5 (117/120)	0.0	0.0 (0/120)	-	1.7 (2/120)	-0.8	95.8 (115/120)	-0.8	7.0	+25.0	32.1	+26.8	45.6	-14.4	0.318	+9.6	14.5	+9.8
FS-PS-FS	97.5 (117/120)	0.0	0.0 (0/120)	-	0.8 (1/120)	0.0	96.6 (116/120)	0.0	5.2	-7.1	24.1	-4.7	53.1	-0.4	0.274	-5.5	12.7	-3.7
FS-FS-FS	97.5 (117/120)		0.0 (0/120)		0.8 (1/120)		96.7 (116/120)		5.6		25.3		53.3		0.290		13.2	
3G/cv. Katchpot 1																		
PS-PS-PS	75.0 (90/120)	+2.3	0.0 (0/120)	-	0.0 (0/120)	0.0	75.0 (90/120)	+2.2	4.8	+4.3	17.0	+6.9	67.7	+26.8	0.315	+26.0	11.2	+30.2
PS-FS-PS	68.3 (82/120)	-6.8	0.0 (0/120)	-	0.0 (0/120)	0.0	68.3 (82/120)	-6.8	3.9	-15.2	12.9	-18.8	61.9	+15.9	0.245	+2.0	8.1	-5.8
FS-PS-FS	81.7 (98/120)	+11.4	0.0 (0/120)	-	1.7 (2/120)	-1.6	80.0 (96/120)	+9.1	4.9	+6.5	18.9	+18.9	65.9	+23.4	0.320	+28.0	12.2	+41.8
FS-FS-FS	73.3 (88/120)		0.0 (0/120)		0.0 (0/120)		73.3 (88/120)		4.6		15.9		53.4		0.250		8.6	
3rd season: 2014- LRS																		
3G/cv. Victoria																		
PS-**PS**-PS	99.2 (119/120)	+3.4	0.0 (0/120)	-	9.2 (11/120)	-6.3	90.0 (108/120)	-2.7	5.3	+8.1	22.9	+5.5	79.4	-3.7	0.425	+3.4	18.3	+2.2
PS-**FS**-PS	98.3 (118/120)	+2.6	0.0 (0/120)	-	10.8 (13/120)	-7.7	87.5 (105/120)	-5.4	5.3	+8.1	22.3	+2.7	85.7	+3.8	0.460	+11.9	19.3	+7.8
FS-**PS**-FS	96.7 (116/120)	+0.8	0.0 (0/120)	-	10.0 (12/120)	-6.8	86.7 (104/120)	-6.3	5.4	+10.2	22.2	+2.3	91.2	+10.5	0.494	+20.1	20.3	+13.4
FS-**FS**-FS	95.8 (115/120)		0.0 (0/120)		3.3 (4/120)		92.5 (111/120)		4.9		21.7		82.5		0.411		17.9	
3G/cv. Katchpot 1																		
PS-**PS**-PS	95.8 (115/120)	+1.7	0.0 (0/120)	-	0.0 (0/120)	0.0	95.8 (115/120)	+1.7	6.1	+3.4	27.9	+4.1	91.8	+0.5	0.554	+1.6	25.4	+4.1
PS-**FS**-PS	87.5 (105/120)	-7.1	0.0 (0/120)	-	0.0 (0/120)	0.0	87.5 (105/120)	-7.1	5.7	-3.4	24.0	-10.4	74.5	-18.4	0.413	-24.2	17.4	-28.7
FS-**PS**-FS	93.3 (112/120)	-0.8	0.0 (0/120)	-	0.0 (0/120)	0.0	93.3 (112/120)	-0.8	5.4	-8.4	24.2	-9.7	101.4	+11.1	0.527	-3.3	23.4	-4.1
FS-**FS**-FS	94.2 (113/120)		0.0 (0/120)		0.0 (0/120)		94.2 (113/120)		5.9		26.8		91.3		0.545		24.4	
4th season: 2015- SRS																		
3G/cv. Victoria																		
PS-PS-**PS**	91.7 (110/120)	-3.5	0.0 (0/120)	-	9.2 (11/120)	-8.4	82.5 (99/120)	-12.3	5.1	+6.2	20.1	-7.3	98.6	+12.9	0.494	+15.2	19.3	+0.5
PS-FS-**PS**	97.5 (117/120)	+2.6	0.0 (0/120)	-	0.0 (0/120)	+0.8	97.5 (117/120)	+3.5	5.3	+10.4	24.6	+13.3	95.7	+9.6	0.509	+18.6	23.7	+23.4
FS-PS-**FS**	97.5 (117/120)	+2.6	0.0 (0/120)	-	1.7 (2/120)	-0.8	95.8 (115/120)	+1.7	4.8	0.0	21.8	+0.5	90.1	+3.2	0.435	+1.3	19.8	+3.1
FS-FS-**FS**	95.0 (114/120)		0.0 (0/120)		0.8 (1/120)		94.2 (113/120)		4.8		21.7		87.3		0.429		19.2	
3G/cv. Katchpot 1																		
PS-PS-**PS**	90.0 (108/120)	-0.9	0.0 (0/120)	-	4.2 (5/120)	-3.4	85.8 (103/120)	-4.6	5.7	-16.2	23.1	-20.6	104.8	+20.8	0.696	+18.9	24.3	-3.2
PS-FS-**PS**	73.3 (88/120)	-19.2	0.0 (0/120)	-	0.0 (0/120)	+0.8	73.3 (88/120)	-18.5	6.8	0.0	23.7	-18.5	88.0	+1.5	0.598	+2.2	20.8	-17.1
FS-PS-**FS**	93.3 (112/120)	+2.7	0.0 (0/120)	-	0.0 (0/120)	+0.8	93.3 (112/120)	+3.7	6.7	-1.5	29.9	+2.7	84.7	+2.3	0.567	-3.1	25.2	+0.4
FS-FS-**FS**	90.8 (109/120)		0.0 (0/120)		0.8 (1/120)		90.0 (108/120)		6.8		29.1		86.7		0.585		25.1	
P-values																		
Selection Treatment (ST)	0.047		-		ns		ns		ns		ns		ns		ns		ns	
Seed Lot (SL)	<0.001		-		0.003		<0.001		ns		ns		ns		ns		ns	
Season (S)	ns		-		ns		ns		ns		ns		<0.001		0.002		0.004	
ST × SL	ns		-		ns		ns		ns		0.005		ns		0.028		<0.001	
ST × S	ns		-		ns		ns		ns		ns		ns		ns		ns	
SL × S	0.001		-		0.027		<0.001		0.009		<0.001		ns		ns		ns	
ST × SL × S	ns		-		ns		ns		ns		ns		ns		ns		ns	

Emergence (%) (plant number emerged/tuber number planted); **Rogued plants** because of bacterial wilt (%) (plant number removed/tuber number planted); **Unaccounted plant loss** (%) (missing number of plants/tuber number planted); **Harvested plants** (%) (plant number harvested/tuber number planted); **Tubers per plant** (# per harvested plant); **Tuber number per m^2** (# m^{-2} planted area); **Weight per tuber** (g/tuber); **Yield per plant** (kg tuber fresh weight/harvested plant); **Yield** (Mg ha^{-1} planted area).

PS positive selection

FS farmers selection

ns non-significant, $P \geq 0.05$

- *P* value could not be obtained because of 0%

Yield per plant. In Experiment 1, the selection treatment × seed lot interaction was significant. In cv. Victoria, yield per plant was higher in PS-FS-PS than the FS-FS-FS treatment, with the other treatments not differing significantly from these extremes, whereas in cv. Katchpot 1, the highest yield per plant was found in the PS-PS-PS treatment, but this yield did only differ significantly from the yield per plant in the PS-FS-PS treatment (Table 4.5). In Experiments 2 and 3, yield per plant was not significantly affected by the selection treatment (Tables 4.3 – 4.5); the average yield per plant across the seed lots was highest in the PS-PS-PS treatment (Experiment 3) and lowest in the FS-FS-FS treatment (Experiment 2), but the differences were not significant (Table 4.5).

Weight per tuber. In Experiment 1, the selection treatment had no influence on weight per tuber (Table 4.5). In Experiment 2, there was a significant interaction between selection treatment and season (Table 4.3, Supplementary Table S4.3B); differences between selection treatments were not consistent across seasons. In the 2nd season, the FS-PS-FS treatment had a higher weight per tuber than the other treatments. In the 3rd season, differences between the selection treatments were not significant. In the 4th season, PS-PS-PS and PS-FS-PS had a higher weight per tuber than FS-PS-FS and FS-FS-FS. In Experiment 3, the selection treatment had a significant effect on weight per tuber, with the weight per tuber being lower in the PS-FS-PS treatment than in the PS-PS-PS and FS-PS-FS treatments and FS-FS-FS not differing significantly from the other treatments.

Tuber number per m^2. In Experiment 1, there was a significant selection treatment × seed lot interaction for number of tubers per m^2. This was mainly caused by the PS-FS-PS treatment producing a relatively high number of tubers per m^2 in the seed lot from cv. Victoria and a relatively low number of tubers in the seed lot from cv. Katchpot 1, whereas the other selection treatments did not differ from each other (Table 4.2, Table 4.5). In Experiment 2, the average number of tubers per m^2 across the seed lots was lower in the FS-FS-FS than in the PS-PS-PS treatment (Table 4.5). Significant interaction of selection treatment × season indicated a higher number of tubers per m^2 in the PS-PS-PS and PS-FS-PS treatments than in the FS-PS-FS and FS-

Table 4.3. Effects of selection treatments, seasons and seed lots on agronomical characteristics in location Kachwekano, Experiment 2 (selection treatment in bold refers to the seed planted in the specific season)

Treatment	Emergence		Rogued plants		Unaccounted plant loss		Harvested plants		Tubers per plant		Tubers per m2		Weight per tuber (g)		Yield per plant (kg)		Tuber yield (Mg/ha)	
Relative change		%		%		%		%		%		%		%		%		%
2[nd] season: 2014- SRS																		
3G/cv. Victoria																		
PS-PS-PS	99.2 (119/120)	+3.4	1.7 (2/120)	-7.2	0.0 (0/120)	-1.7	97.5 (117/120)	+13.6	6.3	+6.7	29.2	+20.6	51.8	-5.6	0.325	+0.6	15.1	+14.3
PS-FS-PS	99.2 (119/120)	+3.4	0.8 (1/120)	-8.2	0.8 (1/120)	-0.8	97.5 (117/120)	+13.6	7.1	+20.3	33.2	+37.2	45.9	-16.4	0.326	+0.9	15.2	+15.1
FS-PS-FS	94.2 (113/120)	-1.7	8.8 (10/120)	0.0	0.0 (0/120)	-1.7	85.8 (103/120)	0.0	6.1	+3.4	24.8	+2.5	61.0	+11.1	0.371	+14.8	15.1	+14.3
FS-FS-FS	95.8 (115/120)		8.7 (10/120)		1.7 (2/120)		85.8 (103/120)		5.9		24.2		54.9		0.323		13.2	
3G/cv. Katchpot 1																		
PS-PS-PS	80.8 (97/120)	+21.2	1.1 (1/120)	+0.8	0.8 (1/120)	+0.8	79.2 (95/120)	+18.7	5.7	+16.3	21.5	+36.1	45.9	-3.7	0.262	+11.5	9.9	+32.0
PS-FS-PS	82.5 (99/120)	+23.7	0.0 (0/120)	0.0	3.3 (3/120)	+2.5	79.2 (95/120)	+18.7	6.2	+26.5	23.4	+48.1	51.8	+8.5	0.323	+37.4	12.2	+62.7
FS-PS-FS	67.5 (81/120)	+1.2	0.0 (0/120)	0.0	0.0 (0/120)	0.0	67.5 (81/120)	+1.2	4.7	-4.1	14.9	-5.7	63.8	+33.7	0.310	+31.9	9.6	+28.0
FS-FS-FS	66.7 (80/120)		0.0 (0/120)		0.0 (0/120)		66.7 (80/120)		4.9		15.8		47.7		0.235		7.5	
3[rd] season: 2014- LRS																		
3G/cv. Victoria																		
PS-**PS**-PS	100.0 (120/120)	+2.5	4.2 (5/120)	0.0	5.0 (6/120)	-0.8	90.8 (109/120)	+3.8	4.9	+13.9	21.3	+17.7	70.9	+14.7	0.353	+32.7	15.2	+36.9
PS-**FS**-PS	98.3 (118/120)	+0.8	2.5 (3/120)	-1.7	0.0 (0/120)	-6.1	95.5 (115/120)	+9.5	4.8	+11.6	21.8	+20.4	71.0	+14.8	0.339	+27.4	15.5	+39.6
FS-**PS**-FS	99.2 (119/120)	+1.7	8.4 (10/120)	+4.3	5.0 (6/120)	-0.8	85.8 (103/120)	-1.9	4.9	+13.9	20.2	+11.6	68.8	+11.3	0.336	+26.3	13.8	+24.3
FS-**FS**-FS	97.5 (117/120)		4.2 (5/120)		5.8 (7/120)		87.5 (105/40)		4.3		18.1		61.8		0.266		11.1	
3G/cv. Katchpot 1																		
PS-**PS**-PS	93.3 (112/120)	+10.9	0.0 (0/120)	-1.6	0.0 (0/120)	0.0	93.3 (112/120)	+13.1	4.9	-3.9	22.0	+10.0	77.8	+4.4	0.383	+2.4	16.9	+14.2
PS-**FS**-PS	95.8 (115/120)	+13.8	2.5 (3/120)	+0.8	0.0 (0/120)	0.0	93.3 (112/120)	+13.1	5.2	+1.9	23.3	+16.5	63.2	-15.2	0.328	-12.3	14.6	-1.3
FS-**PS**-FS	90.8 (109/120)	+7.9	2.7 (3/120)	+0.8	0.0 (0/120)	0.0	88.3 (106/120)	+7.1	4.6	-9.8	19.5	-2.5	75.5	+1.3	0.342	-8.5	14.4	-2.7
FS-**FS**-FS	84.2 (101/120)		1.9 (2/120)		0.0 (0/120)		82.5 (99/120)		5.1		20.0		74.5		0.374		14.8	
4[th] season: 2015- SRS																		
3G/cv. Victoria																		
PS-PS-**PS**	99.2 (119/120)	+5.3	1.7 (2/120)	-13.4	0.0 (0/120)	0.0	97.5 (117/120)	+20.6	4.6	-2.1	21.4	+15.7	88.9	+12.8	0.398	+7.2	18.5	+29.3
PS-FS-**PS**	98.3 (118/120)	+4.4	10.9 (13/120)	-2.9	0.0 (0/120)	0.0	87.5 (105/120)	+8.2	4.4	-6.4	18.6	+0.5	90.1	+14.3	0.390	+5.1	16.4	+14.7
FS-PS-**FS**	97.5 (117/120)	+3.5	4.3 (5/120)	-10.5	0.0 (0/120)	0.0	93.3 (112/120)	+15.4	5.4	+14.8	23.9	+29.2	70.2	-10.9	0.376	+1.3	16.7	+16.7
FS-FS-**FS**	94.2 (113/120)		14.1 (16/120)		0.0 (0/120)		80.8 (97/120)		4.7		18.5		78.8		0.371		14.3	
3G/cv. Katchpot 1																		
PS-PS-**PS**	68.3 (82/120)	-4.6	1.7 (2/120)	-0.8	0.0 (0/120)	0.0	66.7 (80/120)	-3.6	5.7	-9.5	18.5	-11.4	62.0	+26.2	0.345	+11.3	10.9	+6.8
PS-FS-**PS**	79.2 (95/120)	+10.4	0.0 (0/120)	-2.5	0.0 (0/120)	0.0	79.2 (95/120)	+14.4	5.9	-6.3	22.6	+8.1	61.5	+25.2	0.366	+18.1	14.0	+37.2
FS-PS-**FS**	70.0 (84/120)	-2.3	1.7 (2/120)	-0.8	0.0 (0/120)	0.0	68.3 (82/120)	-1.2	6.5	+3.1	21.0	+0.5	56.3	+14.6	0.359	+15.8	11.7	+14.7
FS-FS-**FS**	71.7 (86/120)		2.5 (3/120)		0.0 (0/120)		69.2 (83/120)		6.3		20.9		49.1		0.310		10.2	
P-values																		
Selection Treatment (ST)	<0.001		0.014		ns		<0.001		ns		0.002		ns		ns		<0.001	
Seed Lot (SL)	<0.001		<0.001		0.043		<0.001		ns		0.033		ns		ns		<0.001	
Season (S)	0.015		ns		ns		0.032		ns		ns		0.009		ns		ns	
ST × SL	ns		ns		ns		ns		ns		ns		ns		ns		ns	
ST × S	ns		ns		ns		ns		0.028		0.012		0.004		ns		ns	
SL × S	ns		ns		0.022		0.003		0.035		0.010		0.016		ns		0.044	
ST × SL × S	ns		0.020		ns		0.043		ns		ns		ns		ns		ns	

Emergence (%) (plant number emerged/tuber number planted); **Rogued plants** because of bacterial wilt (%) (plant number removed/tuber number planted); **Unaccounted plant loss** (%) (missing number of plants/tuber number planted); **Harvested plants** (%) (plant number harvested/tuber number planted); **Tubers per plant** (# per harvested plant); **Tuber number per m^2** (# m^{-2} planted area); **Weight per tuber** (g/tuber); **Yield per plant** (kg tuber fresh weight/harvested plant); **Yield** (Mg ha^{-1} planted area).

PS positive selection

FS farmers selection

ns non-significant, $P \geq 0.05$

- *P* value could not be obtained because of 0%

FS-FS treatments in the 2nd season (2014-SRS), whereas differences were not significant in the 3rd season and not found in the 4th season (Table 4.3, Supplementary Table S4.3B). In Experiment 3, the number of tubers per m² was not affected by the selection treatment (Table 4.4, Table 4.5).

Tuber number per plant. In Experiments 1 and 3, the number of tubers per plant was not significantly affected by the selection treatment. In Experiment 2, a significant selection treatment × season interaction indicated more tubers per plant in the 2nd season in the PS-FS-PS treatment than in the other treatments, and no differences between selection treatments in the 3rd season and 4th season (Table 4.3, Supplementary Material Table S4.3B).

Plant numbers. In Experiment 1, there was a significant main effect of the selection treatment on the *number of emerged plants* (Table 4.2). Poor emergence was observed in the PS-FS-PS treatment, mainly in cv. Katchpot 1. No *bacterial wilt* occurred in this experiment; therefore, there was no plant loss due to bacterial wilt (Table 4.2, Table 4.5). No significant effects of the selection treatment could be assessed on *unaccounted loss* and the number of *harvested plants* (Table 4.2, Table 4.5), which was partly influenced by the large variation among individual plots. In some blocks, missing plants tended to occur more frequently in the PS-PS-PS plots, leading also to relatively low numbers of plants harvested in some plots.

In Experiment 2, there were significant main effects of selection treatment on the numbers of *emerged, rogued* and *harvested plants* (Table 4.3, Table 4.5). Across the seed lots, *plant emergence* was higher in the PS-PS-PS and PS-FS-PS treatments than in the FS-PS-FS and FS-FS-FS treatments. *Bacterial wilt* occurred across the seed lots less in the PS-PS-PS and PS-FS-PS treatments (Table 4.3, Table 4.5). The selection treatment had no influence on the *unaccounted loss,* which was less in this experiment than in Experiment 1. Consequently more *plants* were *harvested* in the treatments of PS-PS-PS and PS-FS-PS, compared to FS-PS-FS and FS-FS-FS treatments (Table 4.3, Table 4.5).

In Experiment 3, emergence in general was high and the selection treatment had no clear effect on the *emergence of plants* (Table 4.4, Table 4.5): significant interaction between selection treatment and season was

Table 4.4. Effects of selection treatments, seasons and seed lots on agronomical characteristics in location Hawurma, Experiment 3 (selection treatment in bold refers to the seed planted in the specific season)

Treatment	Emergence		Rogued plants		Unaccounted plant loss		Harvested plants		Tubers per plant		Tubers per m2		Weight per tuber (g)		Yield per plant (kg)		Tuber yield (Mg/ha)	
Relative change		%		%		%		%		%		%		%		%		%
2nd season: 2014- SRS																		
4G UNSPPA/cv. Victoria																		
PS-PS-PS	94.2 (113/120)	-1.7	5.4 (6/120)	0.0	0.0 (0/120)	-2.5	89.2 (107/120)	+0.9	9.0	+13.9	38.7	+16.6	30.5	-12.1	0.259	+0.77	11.1	+1.8
PS-FS-PS	92.5 (111/120)	-3.4	5.4 (6/120)	0.0	5.0 (6/120)	-2.5	82.5 (99/120)	-6.6	8.0	+1.2	31.4	-5.4	34.8	+0.28	0.253	-1.5	9.9	-9.2
FS-PS-FS	93.3 (112/120)	-2.6	4.3 (5/120)	-0.8	6.7 (8/120)	-4.2	82.5 (99/120)	-6.6	8.6	+8.8	33.7	+1.5	32.3	-6.9	0.249	-3.1	9.7	-11.0
FS-FS-FS	95.8 (115/120)		5.2 (6/120)		2.5 (3/120)		88.3 (106/120)		7.9		33.2		34.7		0.257		10.9	
Market/cv. Victoria																		
PS-PS-PS	95.0 (114/120)	-3.4	4.5 (5/120)	-2.7	0.0 (0/120)	-12.1	90.8 (109/120)	+12.3	7.8	+4.0	33.9	+18.9	33.3	+11.0	0.257	+19.5	11.3	+34.5
PS-FS-PS	94.2 (113/120)	-4.2	5.2 (6/120)	-1.8	1.7 (2/120)	-10.2	87.5 (105/120)	+8.2	8.8	+17.3	36.9	+29.4	34.1	+13.7	0.295	+37.2	12.5	+48.8
FS-PS-FS	92.5 (111/120)	-5.9	1.8 (2/120)	-5.3	1.7 (2/120)	-10.2	89.2 (107/120)	+10.3	8.2	+9.3	34.5	+21.1	37.3	+24.3	0.287	+33.5	12.4	+47.6
FS-FS-FS	98.3 (118/120)		6.8 (8/120)		10.8 (13/120)		80.8 (97/120)		7.5		28.5		30.0		0.215		8.4	
5G Farm-saved/cv. Rwangume																		
PS-PS-PS	96.7 (116/120)	0.0	0.8 (1/120)	-2.5	4.2 (5/120)	+3.4	91.7 (110/120)	-0.9	15.7	+9.0	68.5	+7.7	12.2	-5.4	0.190	+2.7	8.3	+1.2
PS-FS-PS	99.2 (119/120)	+2.6	0.0 (0.0/40)	-3.4	2.5 (3/120)	+1.7	96.7 (116/120)	+4.5	15.0	+4.2	69.1	+8.6	12.0	-6.9	0.179	-3.2	8.2	0.0
FS-PS-FS	95.0 (114/120)	+1.7	3.5 (4/120)	-0.0	0.0 (0/120)	-0.8	91.7 (110/120)	-0.9	13.4	+6.9	58.8	-7.5	12.4	-3.8	0.173	-6.5	7.7	-6.1
FS-FS-FS	96.7 (116/120)		3.4 (4/120)		0.8 (1/120)		92.5 (111/120)		14.4		63.6		12.9		0.185		8.2	
3rd season: 2014- LRS																		
4G UNSPPA/cv. Victoria																		
PS-**PS**-PS	92.5 (111/10)	-3.4	4.5 (5/120)	-2.5	1.7 (2/120)	-0.8	86.7 (104/120)	-7.1	5.2	-7.1	21.3	-15.1	102.2	+15.8	0.527	+7.3	21.8	-0.9
PS-**FS**-PS	91.7 (110/120)	-4.3	1.9 (2/120)	0.0	0.0 (0/120)	-0.8	90.0 (108/120)	-3.5	5.5	-1.8	23.6	-5.9	83.1	-5.8	0.450	-8.3	19.5	-11.3
FS-**PS**-FS	98.3 (118/120)	+2.6	2.6 (3/120)	-0.8	0.0 (0/120)	-0.8	95.8 (115/120)	+2.6	4.5	-19.6	20.6	-17.9	101.5	+15.1	0.453	-7.7	20.7	-5.9
FS-**FS**-FS	95.8 (115/120)		1.8 (2/120)		0.8 (1/120)		93.3 (112/120)		5.6		25.1		88.2		0.491		22	
Market/cv. Victoria																		
PS-**PS**-PS	94.2 (113/120)	0.0	0.8 (1/120)	-0.8	0.8 (1/120)	+0.8	92.5 (111/120)	0.0	6.1	+15.1	26.9	+14.9	93.6	+5.0	0.567	+18.1	25.2	+16.1
PS-**FS**-PS	93.3 (112/120)	-0.8	8.9 (10/120)	+6.7	0.0 (0/120)	0.0	85.0 (102/120)	-8.1	6.6	+24.5	26.8	+14.5	80.5	-9.6	0.529	+10.2	21.4	-1.4
FS-**PS**-FS	97.5 (117/120)	+3.5	4.1 (5/120)	+2.5	0.0 (0/120)	0.0	93.3 (112/120)	+0.9	5.1	-3.8	22.7	-2.9	105.1	+17.9	0.540	+12.5	24.1	+11.1
FS-**FS**-FS	94.2 (113/120)		1.8 (2/120)		0.0 (0/120)		92.5 (111/120)		5.3		23.4		89.1		0.480		21.7	
5G Farm-saved/cv. Rwangume																		
PS-**PS**-PS	90.0 (108/120)	-7.7	0.8 (1/120)	-1.7	3.3 (4/120)	+3.3	85.8 (103/120)	-9.6	9.8	-4.8	40.2	-15.9	58.1	+13.7	0.567	+4.8	23.1	-5.7
PS-**FS**-PS	95.0 (114/120)	-2.5	0.8 (1/120)	-1.7	0.0 (0/120)	0.0	94.2 (113/120)	-0.8	8.5	-17.5	38.4	-19.6	52.3	+2.3	0.452	-16.4	20.4	-16.7
FS-**PS**-FS	96.7 (116/120)	-0.8	1.7 (2/120)	-0.8	2.5 (3/120)	+2.5	92.5 (111/120)	-2.6	10.1	-1.9	44.7	-6.5	47.3	-7.4	0.480	-11.3	21.2	-13.5
FS-**FS**-FS	97.5 (117/120)		2.5 (3/120)		0.0 (0/120)		95.0 (114/120)		10.3		47.8		51.1		0.541		24.5	
4th season: 2015- SRS																		
4G UNSPPA/cv. Victoria																		
PS-PS-**PS**	100.0 (120/40)	+2.5	5.8 (7/120)	-6.6	8.3 (10/120)	-3.5	85.8 (103/120)	+6.2	5.2	+1.9	21.4	+8.6	62.4	+6.7	0.325	+6.9	13.2	+12.8
PS-FS-**PS**	100.0 (120/120)	+2.5	8.3 (10/120)	-3.7	5.0 (6/120)	0.0	86.7 (104/120)	+7.2	5.3	+3.9	21.7	+10.1	61.4	+4.9	0.329	+8.2	13.3	+13.6
FS-PS-**FS**	99.2 (119/120	+1.7	5.0 (6/120)	-7.5	0.0 (0/120)	-5.2	94.2 (113/120)	+16.5	5.3	+3.9	23.8	+20.8	60.6	+3.6	0.313	+2.9	14.1	+20.5

FS-FS-**FS**	97.5 (117/120))		11.9 (14/120)		5.0 (6/120)		80.8 (97/120)		5.1		19.7		58.5		0.304		11.7	
Market/cv. Victoria																		
PS-PS-**PS**	96.7 (116/120)	+3.5	9.5 (11/120)	0.0	4.2 (5/120)	-8.4	83.3 (100/120)	+14.9	5.0	-10.7	19.9	+1.0	65.1	+14.0	0.326	+3.2	13.0	+19.3
PS-FS-**PS**	98.3 (118/120)	+5.3	28.7 (34/120)	+21.1	15.8 (19/120)	+4.7	54.2 (65/120)	-25.3	5.9	+5.3	15.4	-21.8	44.3	-22.4	0.263	-16.7	7.0	-35.7
FS-PS-**FS**	96.7 (116/120)	+3.5	8.6 (10/120)	-0.9	5.0 (6/120)	-7.5	83.3 (100/120)	+14.9	4.5	-19.6	17.8	-9.6	58.9	+3.1	0.264	-16.4	10.5	-3.7
FS-FS-**FS**	93.3 (112/120)		9.7 (11/120)		11.6 (14/120)		72.5 (87/120)		5.6		19.7		57.1		0.316		10.9	
5G Farm-saved/cv. Rwangume																		
PS-PS-**PS**	96.7 (116/120)	-2.5	0.8 (1/120)	-2.5	9.2 (11/120)	+6.8	86.7 (104/120)	-7.1	9.4	-3.1	38.9	-10.7	49.9	+8.0	0.464	+5.7	19.2	-1.5
PS-FS-**PS**	97.5 (117/120)	-1.7	3.3 (4/120)	0.0	6.7 (8/120)	+4.2	87.5 (105/120)	-6.2	10.7	+10.3	44.4	+1.8	38.1	-17.5	0.405	-7.7	16.9	-13.3
FS-PS-**FS**	96.7 (116/120)	-2.5	11.1 (13/120)	+7.7	2.5 (3/120)	0.0	83.3 (100/120)	-10.7	9.9	+2.1	39.3	-9.8	46.4	+0.4	0.457	+4.1	18.0	-7.7
FS-FS-**FS**	99.2 (119/120)		3.4 (4/120)		2.5 (3/120)		93.3 (112/120)		9.7		43.6		46.2		0.439		19.5	
P-values																		
Selection Treatment (ST)	ns		ns		ns		ns		ns		ns		0.041		ns		ns	
Seed Lot (SL)	ns		0.011		ns		ns		<0.001		<0.001		<0.001		ns		ns	
Season (S)	0.028		0.008		ns		0.043		0.005		0.002		<0.001		<0.001		<0.001	
ST × SL	ns		0.003		ns		0.005		ns		ns		ns		ns		ns	
ST × S	0.042		ns		ns		ns		ns		ns		ns		ns		ns	
SL × S	ns		ns		ns		ns		ns		ns		0.033		0.040		ns	
ST × SL × S	ns		ns		ns		ns		ns		ns		ns		ns		ns	

Emergence (%) (plant number emerged/tuber number planted); **Rogued plants** because of bacterial wilt (%) (plant number removed/tuber number planted); **Unaccounted plant loss** (%) (missing number of plants/ tuber number planted); **Harvested plants** (%) (plant number harvested/tuber number planted); **Tubers per plant** (# per harvested plant); **Tuber number per m²** (# m^{-2} planted area); **Weight per tuber** (g/tuber); **Yield per plant** (kg tuber fresh weight/harvested plant); **Yield** (Mg ha^{-1} planted area).

PS positive selection

FS farmers selection

ns non-significant, $P \geq 0.05$

- *P* value could not be obtained because of 0%

Table 4.5. Effects of selection treatments in different seed lots on agronomical characteristics in the three experiments. Average values across seasons.

Variate and Selection treatment	Experiment 1, Karengyere			Experiment 2, Kachwekano			Experiment 3, Hamurwa			
	3G/ Cv. Victoria	3G/ Cv. Katchpot 1	Average	3G/ Cv. Victoria	3G/ Cv. Katchpot 1	Average	4GUNSPPA/ Cv. Victoria	Market/ Cv. Victoria	5GFarm saved/ Cv. Rwangume	Average
Fresh tuber yield (Mg/ha)										
PS-PS-PS	17.3 abc	20.3 c	18.8	16.3	12.6	14.4 b	15.4	16.5	16.9	16.3
PS-FS-PS	19.2 bc	15.4 a	17.3	15.7	13.6	14.6 b	14.2	13.7	15.2	14.4
FS-PS-FS	17.6 abc	20.3 c	18.9	15.2	11.9	13.5 b	14.8	15.6	15.6	15.4
FS-FS-FS	16.8 ab	19.4 bc	18.1	12.9	10.8	11.8 a	14.9	13.7	17.4	15.3
P-value	**<0.001**		ns	ns		**<0.001**	ns			ns
Yield per plant (kg/plant)										
PS-PS-PS	0.408 ab	0.489 d	0.448	0.359	0.330	0.344	0.370	0.384	0.407	0.387
PS-FS-PS	0.429 bcd	0.419 abc	0.424	0.352	0.339	0.345	0.344	0.362	0.345	0.351
FS-PS-FS	0.401 ab	0.471 bd	0.436	0.361	0.337	0.349	0.338	0.364	0.370	0.357
FS-FS-FS	0.377 a	0.460 bcd	0.418	0.320	0.307	0.313	0.351	0.337	0.388	0.359
P-value	**0.028**		ns	ns		ns	ns			ns
Weight per tuber (g/tuber)										
PS-PS-PS	75.7	88.1	81.9	70.5	61.9	66.2	65.0	64.0	40.1	56.4 b
PS-FS-PS	75.7	74.8	75.3	69.0	58.8	63.9	59.7	53.0	34.1	48.9 a
FS-PS-FS	78.1	84.0	81.1	66.6	65.2	65.9	64.8	67.1	35.4	55.8 b
FS-FS-FS	74.4	77.1	75.7	65.2	57.1	61.1	60.5	58.7	36.7	52.0 ab
P-value	ns		ns	ns		ns	ns			**0.041**
Tuber number (#/m²)										
PS-PS-PS	23.9 bc	22.7 ab	23.3	23.9	20.7	22.3 bc	27.2	26.9	49.2	34.4
PS-FS-PS	26.4 c	20.2 a	23.3	24.5	23.1	23.8 c	25.6	26.4	50.6	34.2
FS-PS-FS	22.7 ab	24.3 bc	23.5	22.9	18.5	20.7 ab	26.0	25.0	47.6	32.9
FS-FS-FS	22.9 ab	23.9 bc	23.5	20.3	18.9	19.6 a	26.0	23.9	51.7	33.9
P-value	**0.005**		ns	ns		**0.002**	ns			ns

Tubers per plant (#/plant)										
PS-PS-PS	5.5	5.5	5.5	5.3	5.4	5.4	6.5	6.3	11.6	8.1
PS-FS-PS	5.8	5.4	5.6	5.4	5.8	5.6	6.2	7.1	11.4	8.3
FS-PS-FS	5.1	5.7	5.4	5.5	5.3	5.4	6.1	5.9	11.2	7.7
FS-FS-FS	5.1	5.8	5.4	5.0	5.4	5.2	6.2	6.1	11.5	7.9
P-value	---------- ns ----------		ns	---------- ns ----------		ns	---------- ns ----------			ns
Harvested plants %										
PS-PS-PS	90.0	85.6	87.8	95.3	79.7	87.5 b	87.2 bc	88.9 bcde	88.1 bcd	88.1
PS-FS-PS	93.6	76.4	85.0	93.6	83.9	88.7 b	86.4 bc	75.6 a	92.8 ce	84.9
FS-PS-FS	93.1	88.9	90.9	88.3	74.7	81.5 a	90.8 bcde	88.6 bcde	89.2 bcde	89.5
FS-FS-FS	94.4	85.8	90.1	84.7	72.8	78.7 a	87.5 bc	81.9 ab	93.6 cde	87.7
P-value	---------- ns ----------		ns	---------- ns ----------		**<0.001**	---------- **0.005** ----------			ns
Unaccounted loss %										
PS-PS-PS	6.9	1.4	4.2	1.7	0.3	0.9	3.9	1.7	5.6	3.7
PS-FS-PS	4.2	0.0	2.1	0.3	1.1	0.7	3.3	5.8	3.1	4.1
FS-PS-FS	4.2	0.5	2.4	1.7	0.0	0.8	2.2	2.2	1.7	2.0
FS-FS-FS	1.7	0.3	0.9	2.5	0.0	1.3	2.8	7.5	1.1	3.8
P-value	---------- ns ----------		ns	---------- ns ----------		ns	---------- ns ----------			ns
Bacterial wilt rogued plants %										
PS-PS-PS	0.0	0.0	0.0	2.5	0.9	1.7 a	5.2 b	4.9 b	0.9 a	3.7
PS-FS-PS	0.0	0.0	0.0	4.8	0.9	2.8 ab	5.2 b	14.3 c	1.4 a	6.9
FS-PS-FS	0.0	0.0	0.0	7.2	1.7	4.5 bc	3.9 b	4.8 b	5.5 ab	4.8
FS-FS-FS	0.0	0.0	0.0	9.0	1.8	5.4 c	6.3 b	6.1 b	3.1 ab	5.2
P-value		-	-	---------- ns ----------		**0.014**	---------- **0.003** ----------			ns
Emerged plants %										
PS-PS-PS	96.9	86.9	91.9 b	99.4	80.8	90.1 b	95.6	95.3	94.4	95.1
PS-FS-PS	97.8	76.4	87.1 a	98.6	85.8	92.2 b	94.7	95.3	97.2	95.7
FS-PS-FS	97.2	89.4	93.3 b	96.9	76.1	86.5 a	96.9	95.6	96.1	96.2
FS-FS-FS	96.1	86.1	91.1 ab	95.8	74.2	85.0 a	96.4	95.3	97.8	96.5
P-value	---------- ns ----------		**0.047**	---------- ns ----------		**<0.001**	---------- ns ----------			ns

ns=not significant
0.0: no infection took place therefore no analysis was done
Bold significance was used in Results section (*P*-values of the F ratios from ANOVA)

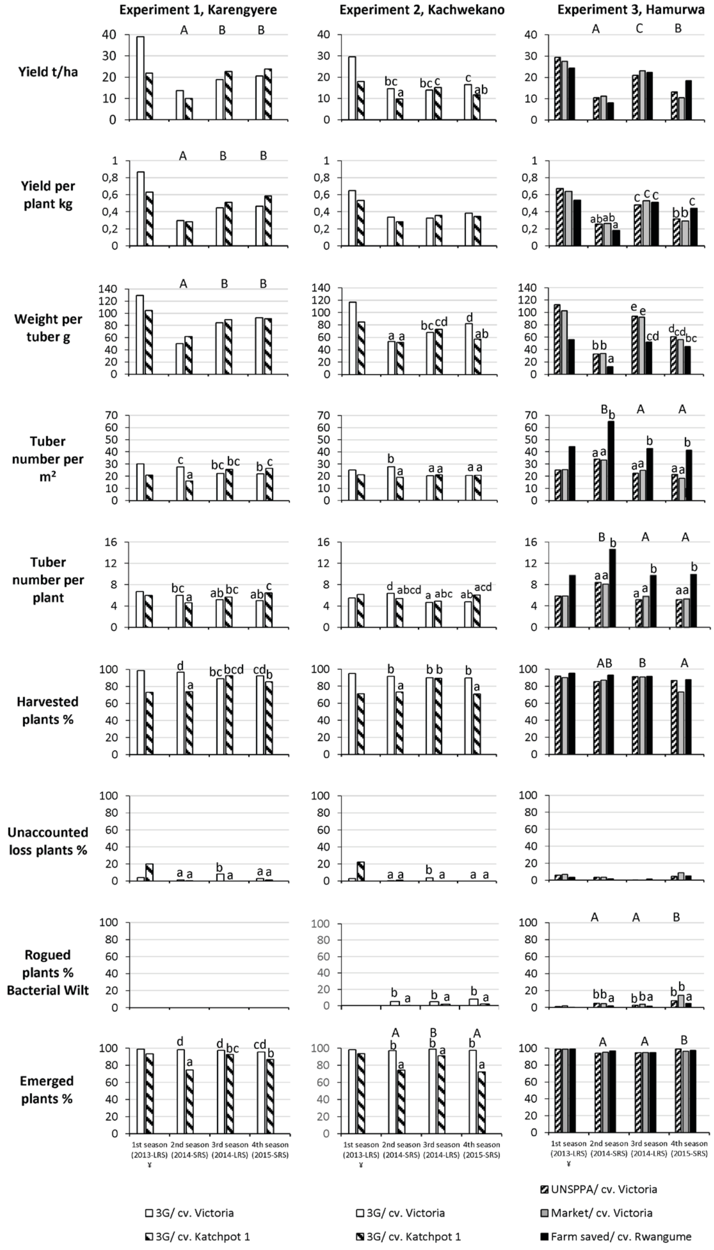

Figure 4.3. Effects of season on tuber yield and yield components of different seed lots in the three experiments; average values across four selection treatments. Different letters indicate significant differences according to Fisher's protected LSD-test (α = 0.05). Capital letters reflect a significant main effect of season; lower case letters reflect a significant season × seed lot interaction. Season 1 data are not part of the statistical analysis because the seeds planted had not yet been subjected to different selection treatments

found but showed no meaningful differences between selection treatments in the different seasons (Supplementary Material Table S4.4B). There was a significant interaction between selection treatment and seed lot on the *number of rogued* and *harvested plants; bacterial wilt* was higher in the PS-FS-PS treatment of cv. Victoria from the market than in all other selection treatments within the two seed lots of cv. Victoria. In cv. Rwangume, the lowest incidence was found in the PS-PS-PS treatment, but effects of the selection treatment on number of rogued plants could not be assessed as significant (Table 4.4, Table 4.5). The selection treatment had no significant effect on the *unaccounted loss,* but the *unaccounted loss* tended to be most frequent in the PS-PS-PS plots for cv. Victoria from UNSPPA and cv. Rwangume (Table 4.4, Table 4.5). A low *number of plants harvested* appeared in cv. Victoria from the market in the PS-FS-PS treatment (Table 4.5), where in the 4th season only 54% of the planted seed potatoes could be harvested (Table 4.4).

4.3.2. Differences between seed lots

Fresh tuber yield per hectare. In Experiment 1, a significant selection treatment × seed lot interaction (Table 4.2) showed that for most selection treatments, there was no significant difference in tuber yield per ha between the seed lots, but that in the PS-FS-PS treatment, yield of cv. Katchpot 1 was lower than that of cv. Victoria (Table 4.5). In Experiment 2, significant seed lot × season interaction showed that tuber yield per ha was lower for cv. Katchpot 1 than for cv. Victoria in the 2nd and 4th seasons, whereas no significant differences in yield per ha between seed lots were found in the 3rd season (Figure 4.3). In Experiment 3, the yield per ha was not significantly different between the three seed lots (Table 4.4, Table 4.5).

Yield per plant. In Experiment 1, a significant selection treatment × seed lot interaction showed a lower yield in cv. Victoria than in cv. Katchpot 1 in the FS-FS-FS and PS-PS-PS treatments, whereas the yield per plant did not differ significantly between seed lots in the other selection treatments (Table 4.5). In Experiment 2, seed lots did not differ in yield per plant (Table 4.3). In Experiment 3, the significant seed lot × season interaction revealed that the seed lots did not differ in yield in the 2nd season and 3rd season, but that the yield of cv. Rwangume was higher than the yield of the two cv. Victoria seed lots in the 4th season (Figure 4.3).

Weight per tuber. In Experiment 1, the seed lot had no influence on the weight per tuber (Table 4.2). In Experiment 2, a significant interaction of seed lot and season showed a higher weight per tuber in cv. Victoria than in cv. Katchpot 1 in the 4th season, whereas there were no significant differences between seed lots in the 2nd and 3rd seasons (Figure 4.3). In Experiment 3, the weight per tuber in cv. Rwangume was significantly smaller than in both seed lots of cv. Victoria in the 2nd and 3rd seasons, whereas in the 4th season, the differences between seed lots in weight per tuber were small and cv. Rwangume still had smaller tubers than cv. Victoria from UNSPPA, but cv. Victoria from the market did not differ significantly from any of the other seed lots (Figure 4.3).

Number of tubers per m^2. In Experiment 1, significant seed lot × selection treatment and seed lot × season interactions (Table 4.2) showed that the difference between seed lots in number of tubers per m^2 depended on season and selection treatment. Cultivar Victoria produced more tubers per m^2 than cv. Katchpot 1 in the PS-FS-PS treatment, whereas no differences between seed lots were found in the other selection treatments (Table 4.5); cv. Victoria also produced more tubers per m^2 than cv. Katchpot 1 in the 2nd season, fewer tubers than cv. Katchpot 1 in the 4th season, and a comparable number of tubers per m^2 in the 3rd season (Figure 4.3). In Experiment 2, the significant seed lot × season interaction showed that tuber numbers per m^2 in the two seed lots differed only in the 2nd season, with more tubers in cv. Victoria than in Katchpot 1 (Figure 4.3). In Experiment 3, the number of tubers in crops from the seed lot of cv. Rwangume was significantly higher than in crops from cv. Victoria (Table 4.4).

Number of tubers per plant. In Experiment 1, the significant seed lot × season interactions showed that more tubers per plant were produced in cv. Victoria than in cv. Katchpot 1 in the 2nd season, while cv. Katchpot 1 produced more tubers than cv. Victoria in the 4th season; no significant differences between seed lots were found in the 3rd season (Figure 4.3). Similar trends were visible in Experiment 2, but differences between seed lots were not significant in any of the seasons (Figure 4.3). In Experiment 3, the number of tubers per plant was higher for cv. Rwangume than for the two seed lots of cv. Victoria in all seasons (Table 4.4, Table 4.5).

Plant numbers. In Experiment 1, the significant seed lot × season interaction showed that the *emergence of plants* was higher for cv. Victoria than for cv. Katchpot 1 in all seasons, but that the difference was most prominent in the 2nd season (Figure 4.3). A significant seed lot × season interaction showed that the *unaccounted loss* was higher in cv. Victoria than in cv. Katchpot 1 in the 3rd season, whereas the *unaccounted loss* was rather small in both cultivars in the 2nd and 4th season (Figure 4.3). A significantly higher number of *plants* were *harvested* in cv. Victoria than in cv. Katchpot 1 (Figure 4.3) in the 2nd and 4th season, but not in the 3rd season.

In Experiment 2, *plant emergence* was higher for cv. Victoria than for cv. Katchpot 1 (Table 4.2, Figure 4.3). *Bacterial wilt* occurred more in cv. Victoria than in cv. Katchpot 1 (Table 4.3, Table 4.5, Figure 4.3). A significant seed lot × season interaction showed that the *unaccounted loss* was higher in cv. Victoria than in cv. Katchpot 1 in the 3rd season, whereas in the other seasons there was no difference between seed lots (Table 4.3). The significant three-way interaction (Table 4.3) showed that the number of *harvested plants* was still higher in cv. Victoria than in cv. Katchpot 1 in for all selection treatments in the 2nd season, and half of the selection treatments (PS-PS-PS and FS-PS-FS) in the 4th season, whereas there were no significant differences between seed lots in harvested plants in the 3rd season and the remaining selection treatments (FS-FS-FS and PS-FS-PS) in the 4th season (Supplementary Material Table S4.3B).

In Experiment 3, seed lot had no effects on the *emergence of plants* or on the *unaccounted loss*, but plant losses due to *bacterial wilt* were higher in the cv. Victoria seed lots than in cv. Rwangume (Table 4.4, Table 4.5). Number of *plants harvested* did not differ among seed lots except in the PS-FS-PS treatment, where the number of *harvested plants* was lower in cv. Victoria from the market than in the other seed lots (Table 4.5).

4.3.3. Seasonal Variation

1st season results

Results of the 1st season are included in Figure 4.3 to show variation across seasons but are not included in the statistical analysis because the seed planted in the first season had not yet been subjected to the experimental selection treatments. In the 1st season, *fresh tuber yield*, *yield per plant* and *weight per tuber* were among the highest found in the four experimental seasons, in all experiments (Figure 4.3). In Experiment 1, cv. Victoria was yielding almost 40 Mg ha^{-1}, double to fourfold of what was found in later seasons. For cv. Katchpot 1 in this experiment, yield in the 1st season was similar to yields in the 3rd and 4th seasons. In Experiment 2, cv. Victoria yielded 30 Mg ha^{-1} in the 1st season, while yield of cv. Katchpot 1 was only slightly higher than in the following seasons. In Experiment 3, yields of 25-30 Mg ha^{-1} in the 1st season were also higher than in later seasons, but only slightly above those in the 3rd season, especially for cv. Rwangume. The data for *number of tubers per m*^{2} and *number of tubers per plant* in the 1st season were of a similar magnitude as the data in the later seasons, except for cv. Rwangume in Experiment 3, which peaked in *number of tubers* in the 2nd season.

In the 1st season, *plant emergence* and *number of harvested plants* were similar to those in the later seasons for seed lots of cv. Victoria in all experiments and of cv. Rwangume in Experiment 3. Emergence rate for cv. Katchpot 1 in Experiments 1 and 2 was comparably high in the 1st season and 3rd season (both LRSs), and higher than in the 2nd and 4th seasons (both SRSs). However, the *harvested plant number* for this cultivar was lower in the 1st season than in the 3rd season in both Experiments 1 and 2 because the *unaccounted loss* was high (20-23%) in the 1st season for cv. Katchpot 1. In the 1st season there were no *rogued plant*s due to bacterial wilt in Experiments 1 and 2 and no to very few *rogued plant*s in Experiment 3.

2nd to 4th season results

Fresh tuber yield per hectare. In Experiment 1, a lower yield for both seed lots was produced in the 2nd season than in the 3rd and 4th seasons (Figure

4.3). In Experiment 2, the significant season × seed lot interaction indicated the yield of cv. Victoria did not differ significantly between the 2nd, 3rd and 4th seasons while the yield of cv. Katchpot 1 was lowest in the 2nd season, highest in the 3rd season, and with the 4th season not differing significantly from the 2nd and 4rd seasons (Figure 4.3). In Experiment 3, lowest yields were produced in the 2nd season, while an increase was achieved in the 3rd season and a decrease obtained in the 4th season, for all seed lots (Figure 4.3).

Yield per plant. In Experiment 1, yield per plant was lower in the 2nd season (Figure 4.3) than in the 3rd and 4th seasons for both seed lots. In Experiment 2, season had no effect on yield per plant. In Experiment 3, the significant seed lot × season interaction indicated that in cv. Rwangume the yield per plant was lower in the 2nd season than in the other seasons (Figure 4.3) whereas in the two seed lots of cv. Victoria yields per plant were higher in the 3rd season than in the 2nd and 4th seasons (Figure 4.3).

Weight per tuber. There was a seasonal effect on weight per tuber in Experiment 1 with a lower weight per tuber in the 2nd season than in the later seasons (Figure 4.3). In Experiment 2, the significant seed lot × season interaction showed that the individual tuber weights were lower in the 2nd season than in the 3rd season for both seed lots, whereas in the 4th season the weight per tuber was higher than in the 3rd season in cv. Victoria, and comparable to the weight per tuber in the 2nd season in cv. Katchpot 1 (Figure 4.3). A significant selection treatment × season interaction (Supplementary Material Table S4.3B) showed a significantly higher weight per tuber in the 3rd and 4th season than in the 2nd season in all selection treatments except FS-PS-FS, where the weight per tuber was relatively high in the 2nd season and did not differ significantly from that in later seasons; weights per tuber did not differ significantly between the 3rd and 4th seasons (Supplementary Material Table S4.3B). In Experiment 3, a significant season × seed lot interaction showed that the weights per tuber were lowest in the 2nd season, especially for cv. Rwangume, and highest in the 3rd season, particularly for both seed lots in cv. Victoria (Figure 4.3), with intermediate values in the 4th season for the cv. Victoria seed lots. In cv. Rwangume, weights per tuber did not differ significantly between the 3rd and 4th seasons.

Number of tubers per m². In Experiment 1, the significant seed lot × season interaction (Table 4.2, Figure 4.3) showed that in cv. Victoria the number of tubers per m^2 did not differ significantly across seasons whereas in cv. Katchpot 1 the number of tubers per m^2 was lower in the 2nd season than in later seasons (Table 4.2, Figure 4.3). In Experiment 2, the significant seed lot × season interaction showed a higher number of tubers per m^2 for cv. Victoria in the 2nd season than in later seasons, whereas in cv. Katchpot 1 the number of tubers per m^2 did not differ significantly in the different seasons (Table 4.3, Figure 4.3). In Experiment 3, the significant main effect of season showed more tubers per m^2 in the 2nd season (2014-SRS) than in later seasons (Figure 4.3).

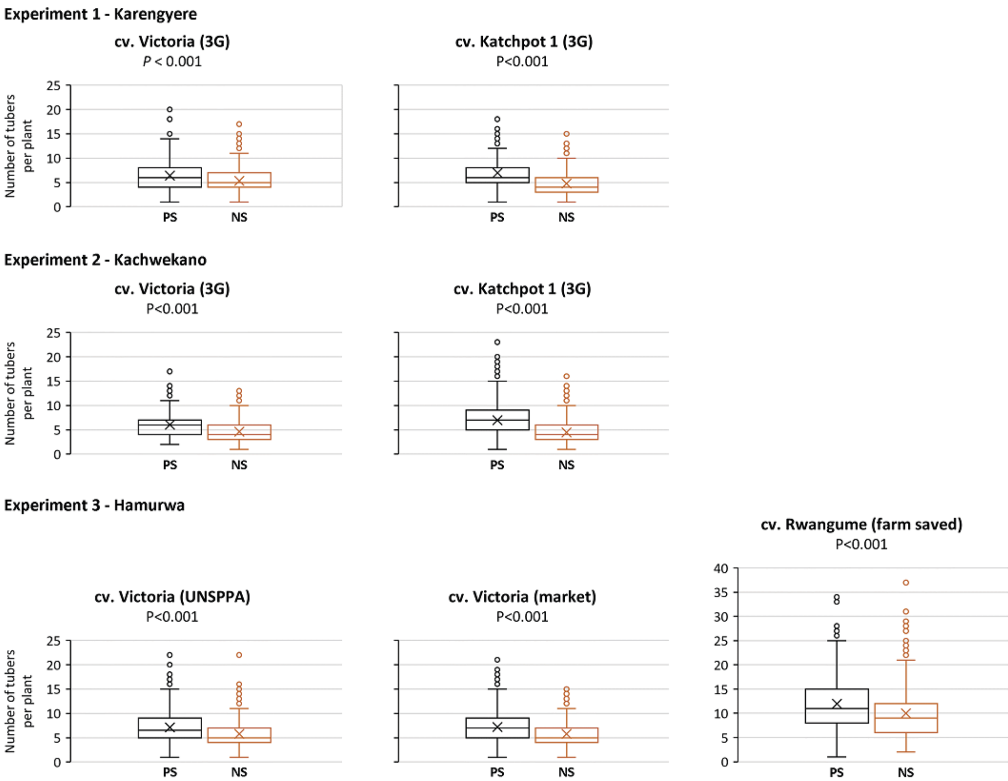

Figure 4.4. Number of tubers per plant from the positive selected (PS) and non-selected (NS) plants in PS plots in all three experiments and all seasons (P-value was obtained from 2-tailed t-test) (Boxplots show the range (rectangles from 25th to 75th percentile), mean (cross), median (line in rectangle), and minimum and maximum values in lines below and above the box, dots are outliers

Number of tubers per plant. In Experiment 1, the significant seed lot × season interaction showed no significant differences in number of tubers per plant between the seasons for cv. Victoria, while for cv. Katchpot 1 a higher number of tubers per plant was found in the 4th season than in the 2nd season, with the 3rd season not differing significantly from the other two (Figure 4.3). In Experiment 2, significant interactions for season × seed lot and season × selection treatment showed higher number of tubers in the 2nd season for cv. Victoria than in later seasons, whereas there were no differences between seasons in number of tubers per plant in cv. Katchpot 1 (Figure 4.3). The number of tubers per plant did not differ between seasons within the individual selection treatments except in the PS-FS-PS treatment that had more tubers per plant in the 2nd season than in later seasons (Supplementary Material Table S4.3B). In Experiment 3, more tubers per plant were found in the 2nd season than in later seasons for all seed lots (Figure 4.3).

Plant numbers. In Experiment 1, the significant seed lot × season interaction showed that *plant emergence* was comparably high over seasons in cv. Victoria whereas a lower *plant emergence* was found for cv. Katchpot 1 in the 2nd season than in the 3rd and 4th seasons (Table 4.2, Figure 4.3). Season had no effect on *bacterial wilt*, because it was always absent in this experiment. A significant seed lot × season interaction showed that the *unaccounted loss* was higher in the 3rd season for cv. Victoria than in the 2nd and 4th seasons, and that there was almost no unaccounted plant loss for cv. Katchpot 1 (Table 4.2, Figure 4.3). Consequently, in the 2nd season, a significantly smaller number of *plants* was *harvested* in cv. Katchpot 1 than in the other seasons, while for cv. Victoria the highest plant number was harvested in the 2nd season, which was similar to the plant number harvested in the 4th season.

In Experiment 2, the significant main effect of season showed higher *plant emergence* in the 3rd season than in the 2nd and 4th seasons (Figure 4.3). The three-way interaction for *rogued plants* (Table 4.4) was due to a high seasonal incidence of bacterial wilt in cv. Victoria in the 4th season in all selection treatments, except in the PS-PS-PS treatment (Figure 4.3, Supplementary Material Table S4.3B). The *unaccounted loss* was only substantial in the 3rd season in cv. Victoria (Figure 4.3) (Table 4.3, Table 4.5). The percentages *plants harvested* for cv. Victoria did not differ significantly across seasons. For cv. Katchpot 1, the 2nd and 4th season showed a significantly smaller number of *plants harvested* than the 3rd season (Figure 4.3).

In Experiment 3, *emergence of plants* across seed lots was higher in the 4th season than in the 2nd and 3rd seasons (Figure 4.3). Incidence of *bacterial wilt* was also higher in the 4th season than in the 2nd and 3rd seasons (Figure 4.3). The *unaccounted loss* was low in all seasons. The 4th season (2015-SRS) had the smallest number of *plants harvested* (Figure 4.3).

4.3.4. Difference in tuber number and tuber weight per plant between positive selected plants and non-selected plants

In those experimental plots in which plants for production of PS seed were selected and other plants remained non-selected, the number of tubers per plant was significantly higher in PS-selected plants than in the non-selected plants in the same plots in all seed lots and experiments (Figure 4.4). Also tuber yield per plant was significantly higher in PS-selected plants than in the non-selected plants, with one exception in Experiment 3 for cv. Victoria from the market, where the difference was not significant (Figure 4.5). In three out of the seven seed lots, a significantly higher weight of large tubers was harvested in positive selected plants than in non-selected plants when tuber yield per plant was divided into classes of large, medium, and small tubers (data not shown).

4.4. Discussion

Our goal was to understand which influence positive seed selection during multiple seasons has on potato yield when compared to farmers' seed selection, and which yield components underlie the differences in yield. Experiments were done under farming conditions in southwestern Uganda and were partly handled by farmers.

Earlier research on the same experiments (Priegnitz et al., 2019b) showed that *virus incidence* in the seed lots fluctuated across seasons, but that continuous PS was able to maintain PLRV and PVX incidence at lower levels than continuous FS. PVA and PVY were only present in the seed lots

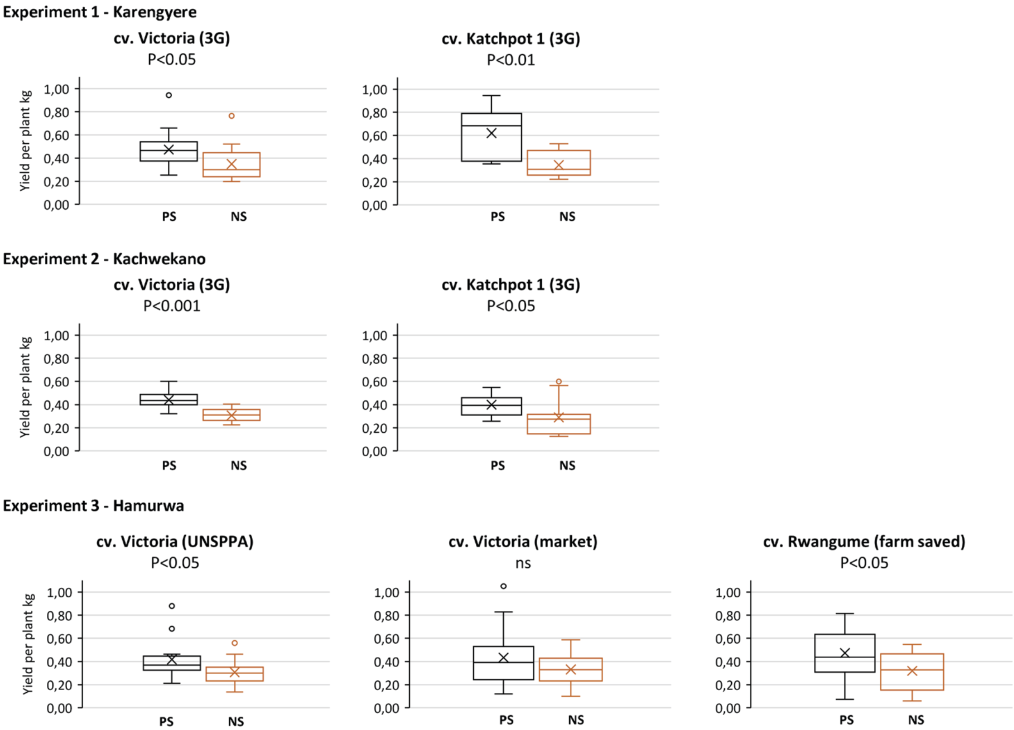

Figure 4.5. Yield per plant (kg) from the positive selected (PS) and non-selected (NS) plants in PS plots in all three experiments and all seasons (P-value was obtained from 2-tailed t-test) (Boxplots show the range (rectangles from 25th to 75th percentile), mean (cross), median (line in rectangle), and minimum and maximum values in lines below and above the box, dots are outliers

at very low levels regardless of the selection treatment. PVS and PVM were present at very high levels in most seed lots, and PS was not more effective than FS in reducing their incidence. The high presence of PVS and PVM resulted in virtually no fully virus-clean plants being present in the seed lots of cv. Victoria, c. 50% clean plants on average in the seed lots of cv. Katchpot 1 and only in the seed lot of cv. Rwangume (Experiment 3) a maximum of more than 90% clean plants was found in the PS treatment in the last season. The high levels of virus present may have hindered the expression of large differences in yield.

This discussion will first focus on these differences in yield between crops under PS and FS and the yield components that underlie these differences. Thereafter potato production and productivity in the experiments under the local conditions will be discussed as well as their implications for the success of positive selection.

4.4.1. Effects of seed selection treatments on tuber yield and its underlying components

Preamble

Under the local farming conditions, yield levels were very variable and plot-to-plot variation was high. The alternating seed selection treatments PS-FS-PS and FS-PS-FS added to this variation; therefore, the discussion will mainly focus on the two most contrasting seed selection treatments, continuously PS (PS-PS-PS) and continuously FS (FS-FS-FS). Figure 4.6 summarizes the differences between PS and FS in yield and related characteristics for all seasons, seed lots and experiments from the data in Tables 4.2 – 4. 4 and Supplementary Tables S4.2A – S4.4A, by plotting the data of the PS treatments against those of the respective FS treatments.

Tuber yield and its components

Yield differences due to seed selection treatments indeed were more difficult to achieve and smaller than expected beforehand. *Tuber yield per ha* can be regarded as a function of the *tuber yield per plant* and the *number of plants harvested*. In all experiments (Table 4.5), the *average tuber yield per ha* was higher in PS-PS-PS treatments than in FS-FS-FS treatments, but under the experimental conditions this positive effect was only significant in Experiment 2, and not that large. Also *tuber yield per plant* seemed consistently, but not significantly, higher under PS than under FS in all experiments (Table 4.5).

When inspecting the size of the differences between continuous PS and FS in detail for all seed lots and individual seasons (Figure 4.6), the *tuber yield per plant* was always higher under PS than under FS (Figure 4.6B). Averaged over all cases, the yield per plant under PS was 9.8% higher than that under FS. The maximum difference was +32.7%, the minimum +0.6% (Table 4.3). For *tuber yield per ha*, Figure 4.6A shows clearly an overall yield increase by PS; on average this yield increase was 12%. This is smaller

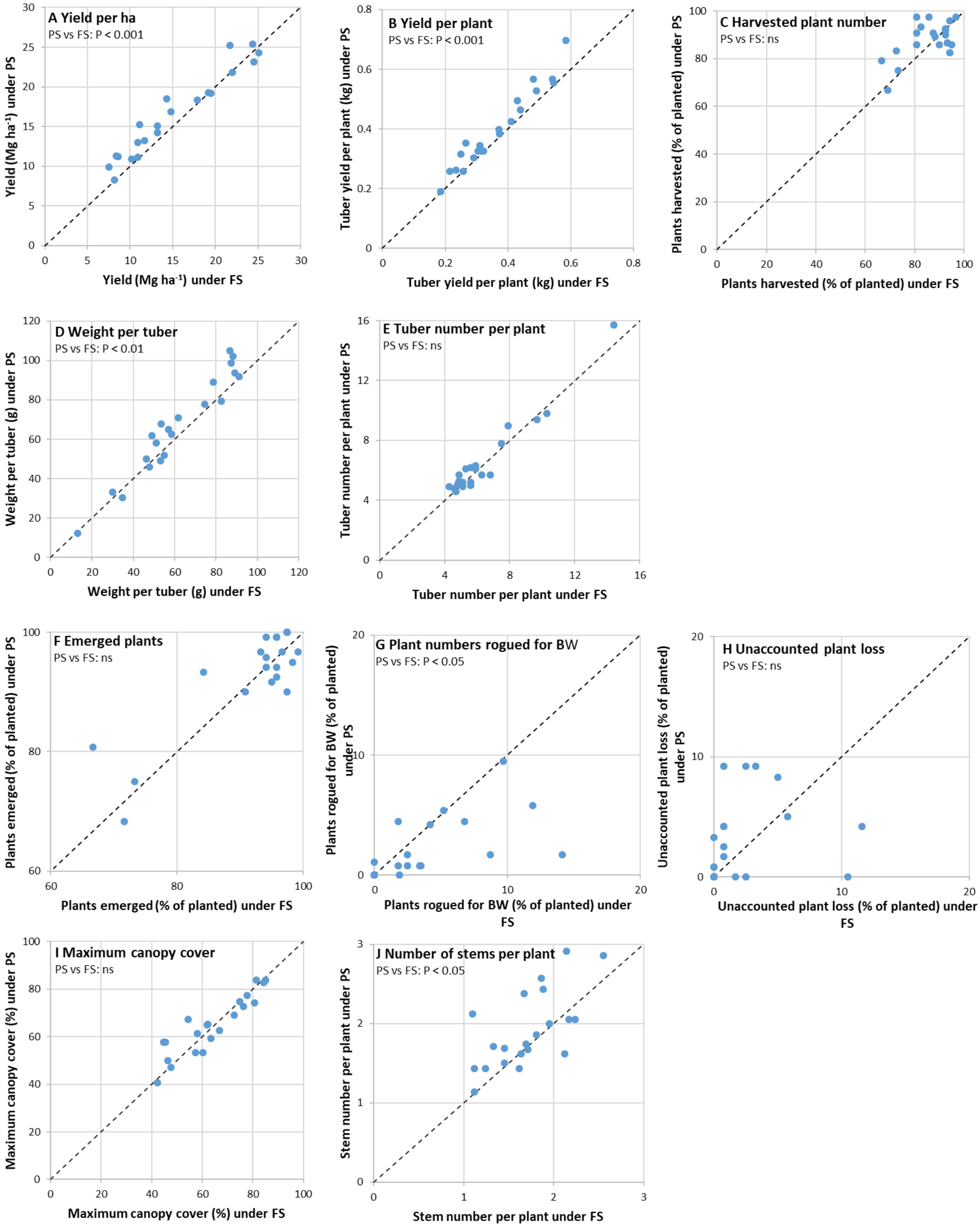

Figure 4.6. Overview of differences between continuously PS and continuously FS in yields and relevant characteristics in all experiments, seasons, and seed lots, based on means from Tables 4.2 -4.4 and Supplementary Tables S4.2A –S4.4A. Dashed lines indicate the 1:1 line where PS would equal FS. Probabilities indicate if the differences between PS and FS were significant according to a paired, two-sided t-test

than the yield increases of around 25 – 30% reported by Gildemacher et al. (2011) and Schulte-Geldermann et al. (2012). This smaller increase will be partly due to the degree to which PS was able to reduce the virus status. Due to the necessity of planting guard rows in an experimental set up, the selection pressure in the present experiments was probably lower than in other conditions (15 plants out of 40 planted tubers were selected to produce seed tubers). The maximum positive difference between crops under PS and FS was +36.9% (Table 4.3). However, Figure 4.6A also shows that in some cases there was no effect of PS and there were even cases where the tuber yields per ha were lower under PS than under FS (Experiment 1, cv. Katchpot 1 in 4th season; Experiment 3, seed lot UNSPAA/cv. Victoria in 3rd and 4th seasons and farm saved/cv. Rwangume in 4th season; Tables 4.2 and 4.4). In all these cases of lower yield per ha, the *plant number harvested* (Tables 4.2 – 4.5; Figure 4.6C) was lower in the PS plots than in the FS plots by an even larger percentage. This shows that the plant number harvested was a variable of considerable importance in determining the yield per ha in this research. In Experiment 2, plant numbers harvested under PS were higher than under FS (Table 4.5), but across all experimental data there was no systematic relation between the plant number harvested under FS and PS ($R^2 = 0.047$) (Figure 4.6C; Table 4.5). We will elaborate on plant numbers below.

The higher *yield per plant* in PS than in FS treatments seemed to be more related to an increase in *weight per tuber* (Figure 4.6D, Table 4.5), by on average 7.4%, than to differences in *number of tubers per plant* (Figure 4.6E, Table 4.5). Under the experimental conditions in Uganda, the number of tubers per plant in most seed lots of cvs Victoria and Katchpot 1 was relatively small with 5.5 tubers per plant.

Reasons for differences in the number of plants harvested

As shown above, the number of plants harvested was of considerable importance in determining the yield per ha and there was no clear direct association between the plant number harvested under PS or FS across experiments (Figure 4.6C). The plant number harvested may therefore vary also for reasons that may or may not be related to the selection treatment. Lower number of harvested plants was caused either by a lower number of *emerged plants*, a higher *plant number rogued* because of bacterial wilt and/ or more plant *losses* due to *unaccounted* reasons, like animal feeding or thefts. Plant emergence was generally variable and, surprisingly, not systematically higher under PS than under FS, except in Experiment 2 where planting PS seed resulted in a higher percentage emergence than planting FS seed (Figure 4.6F). It is not clear to what extent the storage conditions might have affected these differences between experiments. In Experiment 2, the seeds were stored in darkness, in the other experiments under DLS. In Experiment 2, the higher number of emerged plants under PS than under FS (Table 4.5), together with a lower number of plants that had to be rogued because of bacterial wilt in plots under PS, clearly contributed to the higher number of plants harvested under PS than under FS (Table 4.5). The number of plants rogued because of bacterial wilt also in Experiment 3 seemed lower under PS than under FS (Table 4.5, Figure 4.6G). The lower number of plants with bacterial wilt in plots under PS is in line with observations by Gildemacher et al. (2011). Plant losses due to bacterial wilt did not occur in Experiment 1, in Karengyere, the site at the highest altitude of the three locations.

A very important factor determining large variation in number of plants harvested, was the unaccounted loss of plants (Table 4.5). Due to the high variation in plant numbers, the differences between PS and FS in the number of plants lost for unaccounted reasons could not be assessed as significant, but in most cases (but definitively not in all) a higher unaccounted loss appeared in PS plots than in FS plots (Figure 4.6H) which again led to smaller number of plants harvested; the maximum unaccounted plant loss was 22.5% in the 1st season in cv. Katchpot 1 in Experiment 2. We expect the plots under PS showed higher losses because they may have had the most attractive plants.

Effects of positive selection during multiple seasons on yield levels

Most research work thus far was done on effects of PS after one season of selection (e.g. Gildemacher et al., 2011; Schulte-Geldermann et al., 2012). In the present experiments, we particularly wanted to verify if seed tuber health and the yield levels from these seed tubers could be maintained or increased when continuing the selection methods during multiple seasons.

The season itself obviously had a large effect on yield in our research (Figure 4.3), but –during the Seasons 2 – 4 when differently selected seed was compared – there were no indications that the absolute differences in yield per ha or yield per plant between continuous PS or continuous FS increased or decreased when more rounds of selection were applied: there were no significant two-way interactions seed selection method × season for yield per ha or yield per plant, nor significant three-way interactions (Tables 4.2 – 4.4). This is consistent with the effects of PS on the virus status (Priegnitz et al., 2019b). PS seems to be able to keep the virus incidence at a slightly lower level than continuously FS and the yield at a slightly higher level. One case of regeneration was observed, but this was not (only) due to positive selection: cv. Rwangume produced the lowest yield in the 2nd season, when the seed planted had the highest incidence of viruses of all seasons. Cultivar Rwangume regenerated at the end of the experiments in becoming cleaner (Priegnitz et al., 2019b) and more productive in comparison to the other cultivars in this experiment; yet, the PS treatment did not differ significantly from the FS treatment.

It seemed difficult to maintain the yield levels of quality declared seed using PS only. In the 1st season, when the seed used had not yet been subjected to different selection treatments, a considerably higher yield (up to 39 Mg ha^{-1}) was achieved by planting quality declared seed of cv. Victoria (3G seed in Experiments 1 and 2 and 4G-UNSPPA seed in Experiment 3) than in the later Seasons 2 – 4 (Figure 4.3) when the selection treatments that started in Season 1 were continued. Although it cannot be excluded that this higher yield was due to favourable weather or more favourable physiological age of the seed tubers, this cultivar seemed to show clearly the importance of good seed quality in early generations for high productivity, like Schulte-Geldermann et al. (2013) and Demo et al. (2015) described. During the 1st season, plants became more infected by PLRV, PVX and PVA, resulting in a higher virus incidence of the seed tubers produced (Priegnitz et al. 2019b). The yield level of the 3G seed of cv. Katchpot 1 (Experiments 1 and 2) in the 1st season seemed to be sustained when compared to the 3rd and 4th seasons in Experiment 1 (Figure 4.3), but the yield level assessed for this seed lot in the first season was reduced by a high percentage (c. 20%) unaccounted loss of plants.

This suggests that under the present conditions in Uganda with high disease pressure and limited disease control, the seed quality and attainable yield of quality declared seed decrease already during the first multiplication, but that positive selection can keep production thereafter at a higher level than farmers' selection.

4.4.2. Effects of the experimental environment and their implications for yield and the success of positive selection

Potato production and productivity

Our long-term experimental yields ranged from 8.1 Mg ha^{-1} to 39 Mg ha^{-1} with an average of 18.5 Mg ha^{-1} and were much higher than the average yields reported for the country (4.2 Mg ha^{-1}) and the average yields obtained by farmers in the region (9.5 Mg ha^{-1}; Priegnitz et al., 2019a). This might have been due to relatively good crop management practices (van der Zaag 1987), including fertilization of 45 kg N ha^{-1}, spraying against *Phytophthora infestans* and rogueing against bacterial wilt in order to avoid a complete loss of potato plots. It is not known if these relatively good practices may also have reduced the differences between selection treatments. Schulte-Geldermann et al. (2012) showed that under Kenyan conditions, increasing the fertilizer level from 45 to 90 kg N ha^{-1} increased the yield level, but not the absolute difference in yield from PS and FS selected seed.

Despite the relatively good management practices, yield levels obtained in our experiments were still far from maximum, as shown by the low maximum canopy cover during the seasons during which crops from PS and FS selected seeds were compared (Supplementary Tables S4.2A – S4.4A). Due to shortage of precipitation (Table 4.1 and farmers' observation) in the short rainy seasons (2nd and 4th season) the crop suffered a reduction in yield (Experiment 1 (2014-SRS) and Experiment 3 (all SRS's)). Different seasonal weather conditions seemed to exert their effect on yield especially through changing the size of the tubers. Whereas tuber yield per ha, tuber yield per plant and average weight per tuber varied strongly and similarly across seasons, the number of tubers per plant did hardly (Figure 4.3). This is elaborated below.

A very uncertain factor is the physiological age of the seed tubers and how that affected crop production, yield and crop and tuber health. We expect the age to be relatively young, given the short storage duration of 69 – 75 days between harvest and planting. This may have resulted in uneven sprouting, relatively few main stems and probably, but not necessarily, late tuberization. During storage, tubers were covered by grasses, according to the local practices. This was said to enhance sprouting, which supports the idea of a young physiological age of the tubers being a point of attention.

Plant losses

The varying number of plants that was harvested not just greatly increased the plot-to-plot variation and thereby the experimental variation, it also resulted in reduction of the yield levels compared to what would have been possible. Losses were often larger in some plots than in others; in the most extreme case, only 54.2% of planted tubers produced harvested plants. Lower number of harvested plants was caused either by a lower number of *emerged plants*, a higher *plant number rogued* because of bacterial wilt and/or more plant *losses* due to *unaccounted* reasons.

Low plant emergence may have had different reasons. Low emergence was especially found in cv. Katchpot 1 in the short rainy seasons (the 2nd and 4th seasons). The low emergence might be attributed to unfavourable soil conditions (Struik and Wiersema, 1999), like lack of rain and adverse soil structure. Drought during short rainy seasons and more uneven sprouting of some seed tubers might have hindered emergence. Additionally, in some cases, the planting depth used by the farmers to plant the experiments might have been deeper than optimum – which also may have affected emergence. At times, also smaller-sized seed tubers had to be used for planting when there were not enough medium-sized seed tubers from the previous harvest (Table 4.1), and a lower number of plants emerged in the plots when small-sized seed tubers were planted.

During crop growth after emergence, plant losses due to bacterial wilt and/or unaccounted reasons occurred in almost all experiments, seed lots, seasons, and selection treatments. Bacterial wilt losses did not occur in Experiment 1, in Karengyere, the site at the highest altitude of the three locations. In Experiments 2 and 3, losses due to bacterial wilt seemed to increase slightly across the seasons (Figure 4.3), mostly in farmers' selected seed (Figure 4.3, Tables 4.3 and 4.4) and mostly in cv. Victoria (Figure 4.3). The maximum loss due to bacterial wilt was 28.7% in one season in the seed lot of cv. Victoria from the market (Experiment 3). Unaccounted loss of plants, which again led to fewer plants harvested, appeared more frequent in PS plots than in FS plots; the maximum unaccounted loss of plants was 22.5% in the 1st season in cv. Katchpot 1 in Experiment 2.

All these causes of reduction in the plant number will not only decrease fresh tuber yield per ha but also necessitate to select a larger percentage of the remaining plants as source for seed tuber production. Priegnitz et al. (2019b) mentioned a low selection pressure as an important factor for the high virus levels found – next to a high basic virus level and a high transmission risk. The necessity to select a relative large part of the plants adds to reducing this selection pressure.

Tuber number per plant

Whereas tuber yield per ha, tuber yield per plant and average weight per tuber varied strongly across seasons, the number of tubers per plant was relatively stable (Figure 4.3). Under the experimental conditions, per plant only c. 5.5 tubers were produced in the seed lots of cv. Victoria and cv. Katchpot 1, with slightly higher numbers in Exp. 3. Inside a plot in which selection was carried out, the number of tubers per plant was only slightly higher in the selected plants than in the non-selected plants (Figure 4.4); this difference in number was much smaller than the differences in yield per plant (Figure 4.5). A low tuber number might be related to a low stem number due to the relatively physiologically young tubers that had to be planted – with the total period between harvest and planting being only 69 – 75 days. However, stem numbers only seemed to be related to tuber numbers to some extent in Experiment 3, suggesting a maximum number of tubers set per plant in Experiments 1 and 2 regardless of the stem number per plant (Figure 4.7, summarizing data from Tables 4.2 – 4 and Supplementary Tables S4.2A –S4.4A).

The low numbers of tubers per plant have huge consequences for positive selection. The low number of tubers means that, even in the ideal case that all tubers of a plant would be of the desired (medium) size for planting (which is not the case) and all planted tubers will result in harvested plants (which is also not the case), it may be difficult under the present farming conditions in southwestern Uganda, to increase the selection pressure to less than 1 plant out of every 5.5 plants. In our experiments in total 15 out of maximum 40 plants were selected (1 out of 2.7). This can be increased under farmers conditions to some extent (because there is no need for extra experimental tubers to plant the guard rows of the experimental plots) and this may also increase the quality of the seed tubers produced. However, in selecting plants for positive selection, it may not be sufficient to select 10% – 15% of the plants (1 out of 6.7 – 10 plants). This will never lead to enough seed tubers for planting the next crop in cultivars that produce only 5.5 tubers per plant and means that under the conditions leading to this multiplication rate, selection pressure may not be as high as would be desired.

Genotypes with a higher number of tubers per plant (like cv. Rwangume in Experiment 3) can improve the situation but may lead to very small tubers in seasons when yields are low. At this moment insight in the factors determining the stem and tuber number under the local conditions is not complete. Methods to increase the stem and tuber number per plant might be investigated, but they might interfere with the idea of positive selection to be carried out inside a ware potato crop. Nevertheless, the present method of positive selection at the present multiplication rate may already be sufficiently attractive for smallholder farmers as a possibility to increase tuber yield in potato.

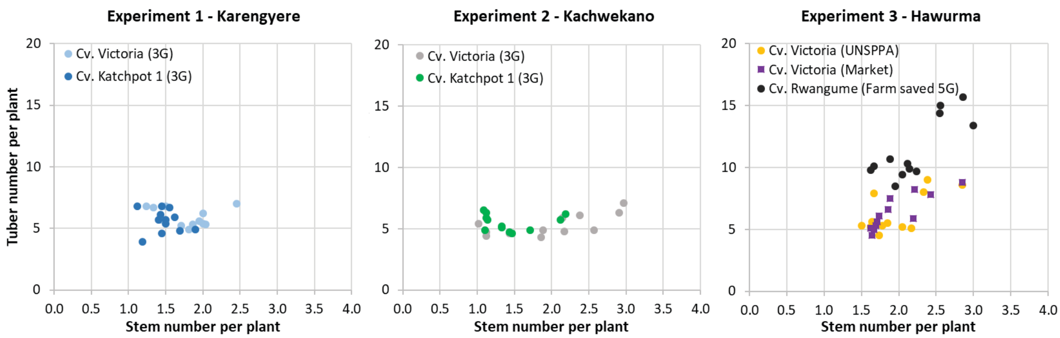

Figure 4.7. Overview of the association between the number of stems per plant and the number of tubers per plant in Experiments 1, 2 and 3, based on means of all selection treatments, seasons and seed lots presented in Tables 4.2 – 4.4 and Supplementary Tables S4.2A –S4.4A

4.4.3. Concluding remarks

Vital points to combat seed degeneration due to high virus pressure in the environment are good seed quality and good crop management, because they determine potato tuber yields (Struik and Wiersema, 1999; Haverkort and Struik, 2015).

Continuous positive selection in multiple seasons was able to maintain yield levels at a higher level than continuous FS. The yield difference in the experiments varied, but was on average 12%. The yield increase by using PS usually resulted from higher yields per plant and in Experiment 2 also from more plants harvested compared to using FS. The higher yields per plant under PS were associated with higher weights per tuber whereas the difference between PS and FS in number of tubers was not significant.

The field experimentation had to deal with a variety of circumstances (bacterial wilt, unaccounted plant loss, little rainfall in the short rainy seasons) due to the "real life" conditions in southwestern Uganda, that limited the exploitation of the full potential of PS. These circumstances affected plant numbers and yield per plant. Crops under PS seemed to suffer more from unaccounted plant losses than crops under FS, but in crops under FS more plants were rogued because of bacterial wilt.

In all experiments, the healthy looking plants chosen for positive selection produced more seed tubers and almost always a higher tuber weight per plant than non-selected plants in the same plot (Figures 4.4 and 4.5) and these tubers also were healthier or less infected (Priegnitz et al. 2019b). This shows the effectiveness of visual inspection. The higher number of tubers in PS selected plants also makes the seed selection process and the multiplication more efficient. This is especially important in cultivars producing only a low number of tubers per plant, like under the investigated conditions cv. Victoria and cv. Katchpot 1.

The trials with good crop management practices showed that yields up to 25 Mg ha $^{-1}$ can be achieved – which are much higher than the national mean yield of 4.2 Mg ha^{-1}. The experiments also showed that when seed tubers from positive selection are planted, an increase in yield can be achieved compared to when tubers from farmers' selection are planted. Positive selection is a tool to fit in the current seed system of southwestern Uganda to lower the degeneration rate in seed potatoes and to gain a higher yield in smallholder potato production.

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Supplementary materials

Table S4.2A Effects of different selection treatments, seasons and seed lots on additional agronomical characteristics in location Karengyere, Experiment 1 (selection treatment in **bold** refers to planted seed). Characteristics are additional to those in Table 4.2.

Treatment	Yield (Mg/ ha planted area)						Canopy cover (maximum %)		Stems per plant	
	Big tubers		Medium size tubers		Small tubers					
Relative change		%		%		%		%		%
2nd season: 2014 –SRS										
3G/cv.Victoria										
PS-PS-PS	3.9	+11.4	7.4	+1.4	2.8	+12.0	50.0	+7.9	2.00	+2.5
PS-FS-PS	3.3	- 5.7	7.9	+8.2	3.2	+28.0	44.0	- 4.9	2.45	+25.4
FS-PS-FS	3.5	0.0	6.5	- 5.4	2.6	+4.0	37.3	- 19.4	1.71	- 12.3
FS-FS-FS	3.5		7.3		2.5		46.3		1.95	
3G/cv. Katchpot 1										
PS-PS-PS	3.7	+60.8	4.6	+12.2	2.9	+38.1	40.7	- 3.8	1.69	+16.5
PS-FS-PS	2.5	+8.7	3.9	- 4.8	1.7	- 19.0	31.0	- 26.7	1.19	- 17.9
FS-PS-FS	4.1	+78.3	5.9	+43.9	2.2	+4.7	48.0	+13.4	1.90	+31.0
FS-FS-FS	2.3		4.1		2.1		42.3		1.45	
3rd season: 2014- LRS										
3G/cv.Victoria										
PS-**PS**-PS	8.2	+1.2	6.9	- 8.0	3.1	+34.8	82.7	- 1.9	1.86	+2.7
PS-**FS**-PS	8.8	+8.6	8.2	+9.3	2.3	0.0	83.3	- 1.2	2.04	+12.7
FS-**PS**-FS	8.9	+9.8	9.1	+21.3	2.4	+4.3	77.3	- 8.3	2.00	+10.5
FS-**FS**-FS	8.1		7.5		2.3		84.3		1.81	
3G/cv. Katchpot 1										
PS-**PS**-PS	12.9	+14.1	8.9	- 13.6	3.5	+25.0	62.7	- 5.9	1.43	- 11.7
PS-**FS**-PS	8.5	- 24.7	5.8	- 43.7	3.1	+10.7	62.0	- 7.0	1.40	- 13.6
FS-**PS**-FS	12.6	+12.5	8.4	- 18.4	2.4	- 14.3	64.0	- 4.0	1.50	- 7.4
FS-**FS**-FS	11.3		10.3		2.8		66.7		1.62	
4th season: 2015- SRS										
3G/cv.Victoria										
PS-PS-**PS**	9.7	+73.2	7.7	- 33.6	1.9	0.0	69.0	- 5.1	1.43	+15.3
PS-FS-**PS**	7.7	+37.5	13.7	+18.1	2.3	+21.0	77.7	+6.8	1.50	+20.9
FS-PS-**FS**	9.2	+64.3	8.8	- 24.1	1.7	+10.5	71.0	- 2.3	1.33	+7.2
FS-FS-**FS**	5.6		11.6		1.9		72.7		1.24	
3G/cv. Katchpot 1										
PS-PS-**PS**	8.8	+8.6	13.1	- 7.1	2.5	- 10.7	65.3	+4.8	1.50	+3.4
PS-FS-**PS**	9.3	+14.8	8.7	- 38.3	2.8	0.0	67.0	+7.5	1.12	- 22.7
FS-PS-**FS**	9.8	+20.9	12.5	- 11.3	2.8	0.0	62.7	+0.6	1.55	+6.8
FS-FS-**FS**	8.1		14.1		2.8		62.3		1.45	

P-values					
Selection Treatment (ST)	ns	ns	ns	ns	ns
Seed Lot (SL)	ns	ns	ns	<0.001	<0.001
Season (S)	ns	0.002	ns	<0.001	0.002
ST × SL	ns	0.005	ns	ns	<0.001
ST × S	ns	ns	ns	ns	ns
SL × S	ns	ns	ns	0.002	0.009
ST × SL × S	ns	ns	ns	ns	0.020

PS positive selection, *FS* farmers selection
ns non-significant, $P \geq 0.05$

Table S4.3A Effects of different selection treatments, seasons and seed lots on additional agronomical characteristics in location Kachwekano, Experiment 2 (selection treatment in **bold** refers to planted seed). Characteristics are additional to those in Table 4.3.

Treatment	Yield (Mg ha^{-1} planted area)						Canopy cover (maximum %)		Stems per plant	
	Big tubers		Medium size tubers		Small tubers					
Relative change		%		%		%		%		%
2nd season: 2014 –SRS										
3G/cv.Victoria										
PS-PS-PS	3.4	+25.9	7.6	- 5.0	4.1	+64.0	67.3	+23.9	2.91	+35.9
PS-FS-PS	3.7	+37.0	7.4	- 7.5	4.0	+60.0	64.0	+17.8	2.97	+38.7
FS-PS-FS	4.6	+70.3	7.1	- 11.2	3.3	+32.0	65.7	+20.9	2.38	+11.2
FS-FS-FS	2.7		8.0		2.5		54.3		2.14	
3G/cv. Katchpot 1										
PS-PS-PS	4.7	+27.0	3.6	+63.6	1.7	+13.3	57.7	+29.1	2.12	+92.7
PS-FS-PS	5.6	+51.3	4.6	+109.1	1.9	+26.7	63.7	+42.5	2.19	+99.1
FS-PS-FS	3.2	+13.5	3.4	+54.5	2.9	+93.3	46.0	+2.9	1.43	+30.0
FS-FS-FS	3.7		2.2		1.5		44.7		1.10	
3rd season: 2014- LRS										
3G/cv.Victoria										
PS-**PS**-PS	8.4	+42.3	5.0	+16.2	1.7	+142.8	74.3	- 7.9	2.57	+38.2
PS-**FS**-PS	8.5	+44.1	5.7	+32.5	1.3	+85.7	83.0	+2.8	2.17	+16.7
FS-**PS**-FS	6.2	+5.1	5.9	+37.2	1.7	+142.8	81.0	+0.4	1.88	+3.2
FS-**FS**-FS	5.9		4.3		0.7		80.7		1.86	
3G/cv. Katchpot 1										
PS-**PS**-PS	10.6	+23.2	5.0	+2.0	1.3	+18.2	65.0	+4.8	1.71	+28.5
PS-**FS**-PS	7.3	- 15.1	5.6	+14.3	1.7	+54.5	66.0	+6.4	1.33	0.0
FS-**PS**-FS	8.1	- 5.8	4.8	+2.0	1.5	+36.4	59.7	- 3.7	1.47	+10.5
FS-**FS**-FS	8.6		4.9		1.1		62.0		1.33	
4th season: 2015- SRS										
3G/cv.Victoria										
PS-PS-**PS**	6.7	+19.6	8.9	+25.3	2.8	+86.7	83.7	+2.9	1.43	+27.7
PS-FS-**PS**	6.2	+10.7	8.2	+15.5	1.9	+26.7	77.3	- 4.9	1.12	0.0
FS-PS-**FS**	5.8	+3.5	8.4	+18.3	2.5	+66.7	88.7	+9.1	1.09	- 2.7
FS-FS-**FS**	5.6		7.1		1.5		81.3		1.12	
3G/cv. Katchpot 1										
PS-PS-**PS**	3.1	+34.8	5.4	- 1.8	2.4	0.0	59.3	- 6.3	1.14	+1.8
PS-FS-**PS**	4.5	+95.6	7.0	+27.3	2.4	0.0	65.0	+2.7	1.12	0.0
FS-PS-**FS**	2.8	+21.7	6.4	- 16.3	1.4	- 41.7	64.0	+1.1	1.09	- 2.7
FS-FS-**FS**	2.3		5.5		2.4		63.3		1.12	

P-values					
Selection Treatment (ST)	0.008	ns	0.002	ns	<0.001
Seed Lot (SL)	ns	0.004	ns	<0.001	<0.001
Season (S)	<0.001	0.014	<0.001	0.009	<0.001
ST × SL	ns	ns	0.043	ns	ns
ST × S	ns	ns	ns	ns	0.015
SL × S					
ST × SL × S					

PS positive selection, *FS* farmers selection
ns non-significant, $P \geq 0.05$

Table S4.4A Effects of different selection treatments, seasons and seed lots on additional agronomical characteristics in location Hawurma, Experiment 3 (selection treatment in **bold** refers to planted seed). Characteristics are additional to those in Table 4.4

Treatment	Yield (Mg ha^{-1} planted area)						Canopy cover (maximum %)		Stems per plant	
	Big tubers		Medium size tubers		Small tubers					
Relative change		%		%		%		%		%
2nd season: 2014 –SRS										
4G UNSPPA/cv. Victoria										
PS-PS-PS	1.5	- 40.0	4.9	+2.1	4.6	+31.4	47.0	- 1.4	2.38	+42.5
PS-FS-PS	2.3	- 8.0	4.7	- 2.1	2.9	- 17.1	47.3	- 0.8	2.33	+39.5
FS-PS-FS	1.9	- 24.0	4.1	- 14.6	3.7	+5.7	49.7	+4.2	2.85	+70.6
FS-FS-FS	2.5		4.8		3.5		47.7		1.67	
Market/cv. Victoria										
PS-PS-PS	3.4	+78.9	5.0	+21.9	2.9	+26.1	57.7	+27.3	2.43	+29.2
PS-FS-PS	3.8	+100.0	5.5	+34.1	3.1	+34.8	57.7	+27.3	2.85	+51.5
FS-PS-FS	3.8	+100.0	5.1	+24.4	3.4	+47.8	55.0	+21.4	2.21	+17.5
FS-FS-FS	1.9		4.1		2.3		45.3		1.88	
5G Farm saved/cv. Rwangume	0.0									
PS-PS-PS		- 100.0	3.8	+11.7	4.5	+15.4	61.3	+5.7	2.86	+12.1
PS-FS-PS	0.5	- 28.5	3.5	+2.9	4.1	+5.1	54.3	- 6.3	2.56	+0.4
FS-PS-FS	0.3	- 57.1	4.1	+20.6	3.2	- 17.9	55.7	- 3.9	3.00	+17.6
FS-FS-FS	0.7		3.4		3.9		58.0		2.55	
3rd season: 2014- LRS										
4G UNSPPA/cv. Victoria										
PS-**PS**-PS	12.2	- 3.2	8.5	+6.2	1.1	+15.4	72.7	- 5.4	1.62	- 1.6
PS-**FS**-PS	12.2	- 3.2	6.0	- 25.0	1.2	- 7.7	76.0	- 0.4	1.85	+12.8
FS-**PS**-FS	12.3	- 2.4	6.5	- 18.7	1.8	+38.4	78.3	+2.6	1.74	+6.1
FS-**FS**-FS	12.6		8.0		1.3		76.3		1.64	
Market/cv. Victoria										
PS-**PS**-PS	15.6	+15.5	8.5	+19.7	1.0	- 9.1	77.3	- 0.5	1.74	+2.9
PS-**FS**-PS	12.3	- 8.8	7.9	+11.3	1.2	+9.1	86.3	+11.1	1.86	+10.1
FS-**PS**-FS	14.7	+8.8	7.2	+1.4	2.1	+90.9	88.0	+13.2	1.62	- 4.7
FS-**FS**-FS	13.5		7.1		1.1		77.7		1.69	
5G Farm saved/cv. Rwangume										
PS-**PS**-PS	9.9	- 5.7	10.3	- 8.8	2.9	+11.5	83.7	- 1.5	1.62	- 23.6
PS-**FS**-PS	9.6	- 8.5	8.9	- 21.2	1.7	- 34.6	77.3	- 9.0	1.95	- 8.1
FS-**PS**-FS	9.6	- 8.5	9.3	- 17.7	2.2	- 15.4	88.3	+3.8	1.67	- 21.2
FS-**FS**-FS	10.5		11.3		2.6		85.0		2.12	

4th season: 2015- SRS										
4G UNSPPA/cv. Victoria										
PS-PS-**PS**	1.6	- 36.0	8.5	+23.2	3.1	+34.8	53.3	- 6.9	2.05	- 5.5
PS-FS-P**S**	3.1	+24.0	8.2	+18.8	1.9	- 17.4	60.7	+5.9	1.78	- 17.9
FS-PS-F**S**	1.9	- 24.0	9.6	+39.1	2.5	+8.7	59.0	+2.9	1.50	- 30.8
FS-FS-**FS**	2.5		6.9		2.3		57.3		2.17	
Market/cv. Victoria										
PS-PS-**PS**	1.8	+38.5	7.7	+4.0	3.4	+54.5	53.3	- 11.7	1.67	- 2.3
PS-FS-**PS**	0.4	- 69.2	4.3	- 41.8	2.3	+4.5	60.7	+0.6	2.19	+28.1
FS-PS-**FS**	1.6	- 23.1	5.8	- 21.6	3.1	+40.9	59.0	- 2.1	1.64	- 4.1
FS-FS-**FS**	1.3		7.4		2.2		60.3		1.71	
5G Farm saved/cv. Rwangume										
PS-PS-**PS**	1.9	- 13.6	11.0	+10.0	6.3	- 12.5	74.7	0.0	2.05	+8.5
PS-FS-**PS**	0.4	- 81.8	7.6	- 24.0	8.9	+23.6	74.0	- 0.9	1.88	- 16.1
FS-PS-**FS**	1.9	- 13.6	11.2	+12.0	4.9	- 31.9	76.0	+1.7	2.14	- 4.5
FS-FS-**FS**	2.2		10.0		7.2		74.7		2.24	
P-values										
Selection Treatment (ST)	ns		0.016		ns		ns		ns	
Seed Lot (SL)	ns		0.002		<0.001		0.044		ns	
Season (S)	<0.001		0.002		<0.001		<0.001		<0.001	
ST × SL	ns		ns		0.004		ns		0.028	
ST × S	ns		ns		ns		ns		0.001	
SL × S	ns		<0.001		<0.001		ns		ns	
ST × SL × S	ns		ns		ns		ns		ns	

PS positive selection, *FS* farmers selection
ns non-significant, $P \geq 0.05$

Table S4.3B Mean separation of significant interactions mentioned in Table 4.3 and Supplementary Table S4.3A that were not presented in Table 4.5 or Figure 4.3 in the main text; location Kachwekano, Experiment 2 (selection treatment in **bold** refers to planted seed)

Treatment	Rogued plants		Harvested plants		Tuber number per plant		Tuber number per m^2		Weight per tuber (g)		Big tuber yield (Mg/ ha)		Stems per plant	
Relative Change		%		%		%		%		%		%		%
2nd season: 2014 –SRS														
3G/cv. Victoria														
PS-PS-PS	1.7 (2/120) ab	- 7.2	97.5 (117/120) gh	+13.6	6.3	+6.7	29.2	+20.6	51.8	- 5.6	3.4 abcdef	+25.9	2.91	+35.9
PS-FS-PS	0.8 (1/120) ab	- 8.2	97.5 (117/120) h	+13.6	7.1	+20.3	33.2	+37.2	45.9	- 16.4	3.7 abcdefg	+37.0	2.97	+38.7
FS-PS-FS	8.8 (10/120) efgh	0.0	85.8 (103/120) cdef	0.0	6.1	+3.4	24.8	+2.5	61.0	+11.1	4.6 abcdefghi	+70.3		+11.2
FS-FS-FS	8.7 (10/120) efgh		85.8 (103/120) cdef		5.9		24.2	2.38	54.9		2.7 ab		2.14	
3G/cv. Katchpot 1														
PS-PS-PS	1.1 (1/120) ab	+0.8	79.2 (95/120) abc	+18.7	5.7	+16.3	21.5	+36.1	45.9	- 3.7	4.7 abcdefghi	+27.0	2.12	+92.7
PS-FS-PS	0.0 (0/120) a	0.0	79.2 (95/120) abc	+18.7	6.2	+26.5	23.4	+48.1	51.8	+8.5	5.6 bdfghij	+51.3	2.19	+99.1
FS-PS-FS	0.0 (0/120) a	0.0	67.5 (81/120) a	+1.2	4.7	- 4.1	14.9	- 5.7	63.8	+33.7	3.2 abcde	+13.5	1.43	+30.0
FS-FS-FS	0.0 (0/120) a		66.7 (80/120) a		4.9		15.8		47.7		3.7 abcdefg		1.10	
3rd season: 2014- LRS														
3G/cv. Victoria														
PS-**PS**-PS	4.2 (5/120) bcdefg	0.0	90.8 (109/120) defg	+3.8	4.9	+13.9	21.3	+17.7	70.9	+14.7	8.4 kmop	+42.3	2.57	+38.2
PS-**FS**-PS	2.5 (3/120) abc	- 1.7	95.5 (115/120) gh	+9.5	4.8	+11.6	21.8	+20.4	71.0	+14.8	8.5 kmop	+44.1	2.17	+16.7
FS-**PS**-FS	8.4 (10/120)cfgh	+4.3	85.8 (103/120) cdef	- 1.9	4.9	+13.9	20.2	+11.6	68.8	+11.3	6.2 ghijklmn	+5.1	1.88	+3.2
FS-**FS**-FS	4.2 (5/120) bcdefg		87.5 (105/40) cdef		4.3		18.1		61.8		5.9 efghijkl		1.86	
3G/cv. Katchpot 1														
PS-**PS**-PS	0.0 (0/120) a	- 1.6	93.3 (112/120) fgh	+13.1	4.9	- 3.9	22.0	+10	77.8	+4.4	10.6 p	+23.2	1.71	+28.5
PS-**FS**-PS	2.5 (3/120) abcd	+0.8	93.3 (112/120) efgh	+13.1	5.2	+1.9	23.3	+16.5	63.2	- 15.2	7.3 ijklmno	- 15.1	1.33	0.0
FS-**PS**-FS	2.7 (3/120) abcde	+0.8	88.3 (106/120) cdef	+7.1	4.6	- 9.8	19.5	- 2.5	75.5	+1.3	8.1 jklmno	- 5.8	1.47	+10.5
FS-**FS**-FS	1.9 (2/120) ab		82.5 (99/120) bcde		5.1		20.0		74.5		8.6 lmnop		1.33	
4th season: 2015- SRS														
3G/cv. Victoria														
PS-PS-**PS**	1.7 (2/120) ab	-13.4	97.5 (117/120) h	+20.6	4.6	- 2.1	21.4	+15.7	88.9	+12.8	6.7 hijklmno	+19.6	1.43	+27.7
PS-FS-**PS**	10.9 (13/120) gh	- 2.9	87.5 (105/120) cdef	+8.2	4.4	- 6.4	18.6	+0.5	90.1	+14.3	6.2 ghijklm	+10.7	1.12	0.0
FS-PS-**FS**	4.3 (5/120) bcdefg	-10.5	93.3 (112/120) fgh	+15.4	5.4	+14.8	23.9	+29.2	70.2	- 10.9	5.8 cdefghijk	+3.5	1.09	-2.7
FS-FS-**FS**	14.1 (16/120) h		80.8 (97/120) abcd		4.7		18.5		78.8		5.6 cdefghij		1.12	
3G/cv. Katchpot 1														
PS-PS-**PS**	1.7 (2/120) ab	- 0.8	66.7 (80/120) a	- 3.6	5.7	- 9.5	18.5	- 11.4	62.0	+26.2	3.1 abcd	+34.8	1.14	+1.8
PS-FS-**PS**	0.0 (0/120) a	- 2.5	79.2 (95/120) abcd	+14.4	5.9	- 6.3	22.6	+8.1	61.5	+25.2	4.5 bcdefgh	+95.6	1.12	0.0
FS-PS-**FS**	1.7 (2/120) ab	- 0.8	68.3 (82/120) a	- 1.2	6.5	+3.1	21.0	+0.5	56.3	+14.6	2.8 abc	+21.7	1.09	-2.7
FS-FS-**FS**	2.5 (3/120 abcdef		69.2 (83/120) ab		6.3		20.9		49.1		2.3 a		1.12	
Selection treatment × Season														
PS-PS-PS × 2nd season					5.98 ab		25.38 bdfg		48.84 a				2.51 fg	

PS-FS-PS × 2nd season			6.67 b	28.29 g	48.86 a		2.58 g
FS-PS-FS × 2nd season			5.43 a	19.82 abc	62.38 c		1.90 de
FS-FS-FS × 2nd season			5.44 a	20.02 abcde	51.29 ab		1.61 cd
PS-PS-PS × 3rd season			4.96 a	21.69 abcdef	74.37 cd		2.14 ef
PS-FS-PS × 3rd season			5.01 a	22.58 abcdefg	67.11 cd		1.75 d
FS-PS-FS × 3rd season			4.77 a	19.88 abcd	72.12 cd		1.67 d
FS-FS-FS × 3rd season			4.70 a	19.03 a	68.18 cd		1.59 bcd
PS-PS-PS × 4th season			5.14 a	19.94 abcd	75.43 d		1.28 abc
PS-FS-PS × 4th season			5.17 a	20.62 abcdef	75.80 d		1.21 ab
FS-PS-FS × 4th season			5.92 ab	22.50 abcdefg	63.25 bc		1.21 ab
FS-FS-FS × 4th season			5.55 ab	19.74 ab	63.96 c		1.16 a
P-values							
Selection Treatment (ST)	0.014	<0.001	ns	0.002	ns	0.008	<0.001
Seed Lot (SL)	<0.001	<0.001	ns	0.033	ns	ns	<0.001
Season (S)	ns	0.032	ns	ns	0.009	<0.001	<0.001
ST × SL	ns	ns	ns	ns	ns	ns	ns
ST × S	ns	ns	0.028	0.012	0.004	ns	0.015
SL × S	ns	0.003	0.035	0.010	0.016	ns	0.012
ST×SL×S	0.020	0.043	ns	ns	ns	0.041	ns

Rogued plants because of bacterial wilt (%) (plant number removed/tuber number planted); **Harvested plants** (%) (plant number harvested/tuber number planted); **Tubers per plant** (# per harvested plant); **Tuber number per m^2** (# m^{-2} planted area); **Weight per tuber** (g per tuber); **Big tuber yield** (Mg ha^{-1} planted area); **Stems per plant** (# per plant).

PS positive selection
FS farmers selection
ns non-significant, $P \geq 0.05$

Table S4.4B Mean separation of significant interactions mentioned in Table 4.4. and Table S4.4A that were not presented in Table 4.5. or Figure 4.3 in the main text; location Hamurwa, Experiment 3 (selection treatment in **bold** refers to planted seed)

Treatment	Emerged plants		Small tubers		Stems/plant	
Relative change		%		%		%
2nd season: 2014 –SRS						
4G UNSPPA/cv. Victoria						
PS-PS-PS	94.2 (113/120)	-1.7	4.6 cd	+31.4	2.38	+42.5
PS-FS-PS	92.5 (111/120)	- 3.4	2.9 ab	- 17.1	2.33	+39.5
FS-PS-FS	93.3 (112/120)	- 2.6	3.7 abcd	- 5.7	2.85	+70.6
FS-FS-FS	95.8 (115/120)		3.5 abc		1.67	
Market/cv. Victoria						
PS-PS-PS	95.0 (114/120)	- 3.4	2.9 abc	+26.1	2.43	+29.2
PS-FS-PS	94.2 (113/120)	- 4.2	3.1 abc	+34.8	2.85	+51.5
FS-PS-FS	92.5 (111/120)	- 5.9	3.4 bcd	+47.8	2.21	+17.5
FS-FS-FS	98.3 (118/120)		2.3 a		1.88	
5G Farm saved/cv. Rwangume						
PS-PS-PS	96.7 (116/120)	0.0	4.5 e	+15.4	2.86	+12.1
PS-FS-PS	99.2 (119/120)	+2.6	4.1 e	+5.1	2.56	+0.4
FS-PS-FS	95.0 (114/120)	+1.7	3.2 d	- 17.9	3.00	+17.6
FS-FS-FS	96.7 (116/120)		3.9 e		2.55	
3rd season: 2014- LRS						
4G UNSPPA/cv. Victoria						
PS-**PS**-PS	92.5 (111/40)	- 3.4	1.1 cd	+15.4	1.62	- 1.6
PS-**FS**-PS	91.7 (110/120)	- 4.3	1.2 ab	- 7.7	1.85	+12.8
FS-**PS**-FS	98.3 (118/120)	+2.6	1.8 abcd	+38.4	1.74	+6.1
FS-**FS**-FS	95.8 (115/120)		1.3 abc		1.64	
Market/cv. Victoria						
PS-**PS**-PS	94.2 (113/120)	0.0	1.0 abc	- 9.1	1.74	+2.9
PS-**FS**-PS	93.3 (112/120)	- 0.8	1.2 abc	+9.1	1.86	+10.1
FS-**PS**-FS	97.5 (117/120)	+3.5	2.1 bcd	+90.9	1.62	- 4.7
FS-**FS**-FS	94.2 (113/120)		1.1 a		1.69	
5G Farm saved/cv. Rwangume						
PS-**PS**-PS	90.0 (108/120)	- 7.7	2.9 e	+11.5	1.62	- 23.6
PS-**FS**-PS	95.0 (114/120)	- 2.5	1.7 e	- 34.6	1.95	- 8.1
FS-**PS**-FS	96.7 (116/120)	- 0.8	2.2 d	- 15.4	1.67	- 21.2
FS-**FS**-FS	97.5 (117/120)		2.6 e		2.12	
4th season: 2015- SRS						
4G UNSPPA/cv. Victoria						
PS-PS-**PS**	100.0 (120/120)	+2.5	3.1 cd	+34.8	2.05	- 5.5
PS-FS-P**S**	100.0 (120/120)	+2.5	1.9 ab	-17.4	1.78	- 17.9
FS-PS-F**S**	99.2 (119/120)	+1.7	2.5 abcd	+8.7	1.50	- 30.8
FS-FS-**FS**	97.5 (117/120)		2.3 abc		2.17	
Market/cv. Victoria						
PS-PS-**PS**	96.7 (116/120)	+3.5	3.4 abc	+54.5	1.67	- 2.3
PS-FS-**PS**	98.3 (118/120)	+5.3	2.3 abc	+4.5	2.19	+28.1
FS-PS-**FS**	96.7 (116/120)	+3.5	3.1 bcd	+40.9	1.64	- 4.1
FS-FS-**FS**	93.3 (112/120)		2.2 a		1.71	
5G Farm saved/cv. Rwangume						
PS-PS-**PS**	96.7 (116/120)	-2.5	6.3 e	-12.5	2.05	+8.5
PS-FS-**PS**	97.5 (117/120)	-1.7	8.9 e	+23.6	1.88	- 16.1
FS-PS-**FS**	96.7 (116/120)	-2.5	4.9 d	-31.9	2.14	- 4.5
FS-FS-**FS**	99.2 (119/120)		7.2 e		2.24	
Selection treatment × Season						
PS-PS-PS × 2nd season	79.15 abcd				2.55 c	
PS-FS-PS × 2nd season	79.24 abcd				2.57 c	
FS-PS-FS × 2nd season	76.44 ab				2.69 c	
FS-FS-FS × 2nd season	81.22 bcde				2.03 b	
PS-PS-PS × 3rd season	74.19 a				1.65 a	
PS-FS-PS × 3rd season	77.09 abc				1.88 ab	
FS-PS-FS × 3rd season	85.53 e				1.67 a	

FS-FS-FS × 3rd season	81.75 bcde		1.81 ab
PS-PS-PS × 4th season	85.08 de		1.92 ab
PS-FS-PS × 4th season	83.34 de		1.95 ab
FS-PS-FS × 4th season	82.66 cde		1.76 ab
FS-FS-FS × 4th season	82.58 cde		2.04 b
P-values			
Selection Treatment (ST)	ns	ns	ns
Seed Lot (SL)	ns	<0.001	ns
Season (S)	0.028	<0.001	<0.001
ST × SL	ns	0.004	0.028
ST × S	0.042	ns	0.001
SL × S	ns	<0.001	ns
ST×SL×S	ns	ns	ns

Emergence (%) (plant number emerged/tuber number planted); **Small tubers yield** (Mg ha planted area); **stems per plant**.

PS positive selection
FS farmers selection
ns non-significant, $P \geq 0.05$

CHAPTER 5

Economic evaluation of applying positive seed selection in potato production in different farm types in Uganda

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Abstract

Potato production in southwestern Uganda is crucial for food security and profitable for cash security. However, potato yields remain low and are constrained by lack of good quality seed potatoes. Positive seed selection is a technique for cash-poor smallholder farmers to maintain seed potato productivity and slow down (or even reverse) the process of seed degeneration. Data from a smallholder farm survey (n=259) were analysed and four farm types differing in uptake of innovation practices were used for an economic analysis of using positive selection. This research showed that farms that already adopted positive selection, invested on average 1.2 extra days (i.e. 2.7 extra labourer days) per acre in positive selection, with an average of 4.0% extra labour costs. A scenario study among the non-adopters of positive selection, assuming a 10% extra yield by carrying out positive selection, showed that a marginal rate of return of adopting positive selection of far above 100% was achieved in every farm type. Gross and net benefit varied because of different yield increases and different selling prices of potatoes in the different farm types, indicating that some farm households benefitted more than others. However, the results indicated that positive seed selection can be a valuable option for cost effective seed potato production management in the informal seed sector in Uganda.

Keywords cost-benefit analysis · farm typology · positive seed selection · seed potato economics · *Solanum tuberosum* · Uganda

5.1. Introduction

Potato (*Solanum tuberosum* L.) is the third most important root and tuber crop after cassava and sweet potato regarding food security and cash income in Uganda (Gildemacher et al., 2009; Okoboi et al., 2014; Tatwangire and Nabukeera, 2017; Kyomugisha et al., 2018). The production zones of potato are mainly in the highlands of Uganda, largely in Kabale and Kisoro districts, where the major part of the crop is grown (Kaguongo et al., 2008; Bonabana-Wabbi et al., 2013; Ugandan Bureau of Statistics, 2017). While there is limited availability of arable land and the demand in Uganda for potatoes is rising, there is a need to increase production and yield (Gildemacher et al., 2009). The total potato production in Uganda is reported to be 165,000 Mg on 39,300 ha, indicating that the average potato yields is only 4.2 Mg ha^{-1} (Food and Agriculture Organization of the United Nations, 2018). A potato yield of 25 Mg ha^{-1} could be attained (International Potato Center, 2011).

Kaguongo et al. (2008) and Gildemacher et al. (2011) showed in their studies that the low yields were caused by poor adoption of good management practices. In Uganda, potato management practices are carried out by manual labour, mainly with a hoe, and no mechanisation or draught animals are involved in potato production. Rates of fertiliser, fungicide and pesticide application vary among farmers (Okoboi et al., 2014), but are generally low. Another key cause for the low yield, however, is planting low quality seed tubers (Struik and Wiersema, 1999; Wang'ombe and van Dijk, 2013; Thomas-Sharma et al., 2016).

Uganda does not have a well-functioning formal seed system for potato and the current systems are mainly organised through self-supply. Quality-declared potato seed is available in Uganda, but it is far too costly for smallholder farmers with 130,000 UGX (50 US Dollar) per 80-kg bag. Despite the high cost, the demand is often higher than the supply (CTA, 2014; Kakuhenzire et al., 2015). In the current informal seed systems, farmers recycle their seed tubers over several seasons and generations, by selecting seed tubers from the tubers of their previous ware potato harvest (farmers' selection); therefore, no seed costs are involved. These recycled seed potato tubers transmit diseases and pests to the next crop and next generation of tubers, and seed tuber lots subsequently become degenerated over time. This reduces the productivity of the crop (Struik and Wiersema, 1999; Thomas-Sharma et al., 2016; Priegnitz et al., accepted)

One technique to slow down the process of degeneration and to improve seed potato quality is the technique of positive selection (Schulte-Geldermann et al., 2012; Priegnitz et al., 2019b). In positive selection, the healthiest looking plants are marked in the field around flowering by means of pegs, checked for lack of disease symptoms thereafter, and harvested separately; the tubers from these plants are then used in the next season as seed tubers. Positive selection can enhance crop health and productivity because less diseased seed tubers are planted compared to farmers' selection. It may even be possible to regenerate seed as not all daughter tubers are becoming virus infected (Bertschinger et al., 2017). However, positive selection involves extra labour for marking healthy plants, checking their health status at harvest, separately harvesting their tubers and separately storing these seed tubers. It might also require a cash investment for pegs. Farmers might not always be willing or able to make these extra labour or cash investments.

The objective of this study is (a) to assess the time, labour and costs of positive selection invested by farmers in southwestern Uganda who carry out positive selection, (b) compare these costs and labour data to those of other practices and (c) to explore if it is economically feasible for non-adopters of positive selection to invest in this technique to achieve a higher crop yield. Earlier research had shown that farms in this region differed in uptake of innovative practices and simultaneously potato yield and wealth status (Priegnitz et al., 2019a); farms therefore may also differ in the ability to adopt positive selection. Therefore, to verify if results apply in general, the present study was conducted for potato farms in four types differing in the above-mentioned characteristics.

5.2. Materials and methods

Data collection

The primary data was generated from a semi-structured questionnaire administered among 259 potato smallholder farms in June 2014, in Kabale and Kisoro districts in southwestern Uganda, the districts in which most of the potato in Uganda is grown. Information obtained, beside others, included applied agricultural management practices, duration per management practice in days per acre, number of hired and family labourers per day and their costs, agricultural input use and agricultural input costs, potato yield and selling price per 100-kg bag of potatoes. Under the local conditions, farmers calculate input in units per acre and yields in 100-kg bags per acre. The average area under potato was 1.88 acres (0.76 ha). Therefore, presented data is based on acres until the final recalculation of total costs on a per ha basis. More information on the survey can be found in Priegnitz et al. (2019a).

Main characteristics in different farm types

From the same survey, Priegnitz et al. (2019a) developed four farm types (FT) based on differences in adoption of innovations. FT 1 (n=104) was characterised as innovative farms with second highest yield, FT 2 (n=63) were highly innovative farms with also the highest yield, FT 3 (n=38) were semi-innovative farms with second lowest yield, and FT 4 (n=53) were low innovative farms with little adoption of new practices and lowest potato yield (Table 5.1). Those farm types varied among others in return of potato farming, access to extension service and knowledge, socio-economic characteristics, potato framing attributes and use of agricultural inputs (Table 5.1); they provide a realistic situation of the heterogeneity of farm types. Uptake of positive selection and the related seed plot technique was higher in FT 2 and FT 3 than in FT 1 and FT 4.

Labour use and agricultural input costs for individual management practices including positive selection

Labour days for positive selection and each of six main management practices (1^{st} land ploughing, 2^{nd} land ploughing, planting, weeding, spraying and harvesting) were calculated from the duration of the operation in days per acre and the number of hired and family labourers used per day per acre. Total labour days were the sums of hired and family labour days. Costs of each labour type per operation were calculated from the labour days and the

Table 5.1. Characteristics of farms and the four identified farm types including the p-value of one-way analysis of variance of differences between farm types. Data from Priegnitz et al., 2019b, with permission.

Category and characteristic[1]	Mean (n= 259)	FT 1 (n=104) Innovative farms	FT 2 (n=64) Highly innovative farms	FT 3 (n=38) Semi-innovative farms	FT 4 (n=53) Low innovative farms	p-value
Fraction of farms that took up innovations in potato farming						
Use of fertilizer	0.55	**0.63 b**	**0.59 ab**	**0.42 a**	**0.43 a**	0.030
Use of organic input	0.41	**0.42 b**	**0.48 bc**	**0.61 c**	**0.17 a**	0.000
Use of fungicide	0.72	**0.87 c**	**0.98 d**	**0.03 a**	**0.60 b**	0.000
Use of pesticide	0.73	**0.97 c**	**0.77 b**	**1.00 c**	**0.00 a**	0.000
Use of SPT or PS	0.37	**0.02 a**	**0.69 c**	**0.63 c**	**0.23 b**	0.000
Use of quality declared seed	0.15	**0.05 a**	**0.48 b**	**0.00 a**	**0.04 a**	0.000
Use of sole cropping	0.58	**0.53 a**	**0.82 b**	**0.52 a**	**0.41 a**	0.000
Number of innovations	3.5	**3.5 b**	**4.8 c**	**3.2 b**	**1.8 a**	0.000
Return of potato farming						
Yield in Mg ha^{-1}	9.49	**10.3 bc**	**10.8 c**	**8.3 ab**	**7.2 a**	0.001
Price per 100-kg bag in UGX	69,913	**71,759 bc**	**73,371 c**	**66,891 ab**	**64,019 a**	0.001
Fraction of farms with access to extension service and knowledge						
Advisory service	0.68	**0.72 b**	**0.93 c**	**0.57 ab**	**0.41 a**	0.000
NAADS	0.56	**0.57 b**	**0.78 c**	**0.50 ab**	**0.34 a**	0.000
Farm Group	0.71	**0.72 b**	**0.92 c**	**0.78 bc**	**0.50 a**	0.000
Years of farming potato	13.23	14.8	13.1	12.0	12.3	0.224
Socio-economic characteristics						
Characteristics of the farm household						
Household size total	6.4	6.7	6.6	6.5	5.7	0.118
Respondent's age	42.6	42.4	44.7	41.4	41.0	0.380
Respondent's education	0.25	0.21	0.34	0.18	0.28	0.180
Acres in ownership[2]	2.30	**2.27 ab**	**2.89 b**	**1.73 a**	**1.83 a**	0.015
Total acres of farmland[2]	2.66	2.66	3.24	2.31	2.21	0.068
Labour in potato farming						
Hired labour: average number of labourers per practice	6.34	**6.4 ab**	**7.8 b**	**6.1 ab**	**4.9 a**	0.004

Family labour: average number of labourers per practice	1.98	1.9	2.1	1.9	1.8	0.691
Potato farming areas and seasons						
Acres potato per year[2]	1.88	**1.97 b**	**2.27 b**	**1.96 ab**	**1.36 a**	0.015
Potato in long season (fraction farms)	0.84	0.79	0.90	0.86	0.86	0.263
Potato in short season (fraction farms)	0.91	0.92	0.93	0.89	0.90	0.865
Potato in off-season (fraction farms)	0.47	**0.46 ab**	**0.62 b**	**0.44 ab**	**0.37 a**	0.047
Knows about SPT and/or PS (fraction farms)	0.68	0.64	0.75	0.67	0.67	0.565
Last two seasons quality declared seed (fraction farms)	0.11	**0.04 a**	**0.34 b**	**0.00 a**	**0.03 a**	0.000

Means with different *letter*s in a row indicate significant difference ($p < 0.05$) according to Fisher's LSD test

[1] For full explanation of the characteristics, see Priegnitz et al., 2019b

[2] The number of respondents underlying the mean was different from n=259; for exact numbers see Priegnitz et al., 2019b

costs per day. The costs of hired labour were derived from what a respondent mentioned to pay to one labourer for one day of work. Opportunity costs per day for family labourers were also derived from the survey; the respondent gave for each practice a monetary value for one day of work when a family member worked on their farm. Total labour costs were the sums of the hired and family labour costs. To derive costs per hectare the costs per acre were multiplied by 2.47 (one hectare equals 2.47 acres).

Some farm households did not carry out certain pre- or post-planting farm practices (or information could not be obtained). To calculate the *inputs and costs of the individual practices*, only data from those farms that applied the practices were used. Some farm households applying a certain practice were using only one of the labour types for a specific practice, while some farm households used both labour types. In the cost calculation, the fractions of farms using a certain type of labour are provided, but the data on hired and family labour were calculated as averages across all farms applying a management practice, including those that may not have used a specific labour type.

Agricultural input costs per ha of the farms using the inputs were derived from the quantities and prices per unit a farmer used on one acre. Some farm households did not use any agricultural inputs, while some farms applied, e.g., only one agricultural input. The main source of potato seed tubers used by the smallholder farmers was seed saved from the bulk of their harvest, therefore no seed costs accrued; in later cost-benefit analyses, a seed input rate of 1.5 Mg ha^{-1} was subtracted from the main yield of all farms.
All cost and benefit results were expressed in Ugandan Shillings and in US Dollars (exchange rate 30^{th} June 2014: 1 USD = 2600 UGX).

Costs of positive selection

The costs of positive selection per ha were calculated from the farms that already applied positive selection within the four farm types as described above. Labour and costs of carrying out positive selection were then compared to the (labour and) costs of carrying out the other main management practices. Additionally, the labour and costs of positive selection were compared to the total other labour costs at the farms that applied positive selection. For this, the investment in labour for positive selection was calculated as percentage of the other labour (total labour costs minus positive selection) of those farms. In this study, sticks for marking and labelling the selected plants are often gathered around the field and do not require an expense per se. Cutting sticks requires additional labour. However, this is not considered separately.

Economic feasibility for non-adopters of investing in positive selection

To evaluate the economic applicability and feasibility for non-adopters of positive selection to invest in positive selection, first a cost-benefit analysis was carried out for the present situation of the non-adopters of either positive selection or the seed plot technique and the present *rate of return* of growing potato without positive selection was calculated. Thereafter the *marginal rate of return* of investing in positive selection was calculated in case of a scenario of investing in positive selection. Finally, a new (adjusted) cost-benefit analysis and a new (adjusted) rate of return were calculated and compared to the present situation.

For calculating the field benefits, first the *profitable yield* was derived from the *total yield* which a farmer obtained minus a *seed rate for planting* the next season crop of 1.5 Mg ha^{-1}. From the profitable yield and the *selling price of the potatoes* the *gross benefit* was calculated. *Net benefit* was calculated as the gross benefit minus *total costs of inputs, hired labour and family labour*. *Input costs* (fertilizer, pesticides, fungicides) were calculated from the actual units a farm used. All costs were derived from summing up the costs for the individual combinations of practices carried out on farms. For this analysis, fixed costs like for example, land and tools, were not considered.

To determine the feasibility for non-adopters of investing in positive selection, a scenario was calculated then for farms in the different types that had not adopted positive selection (and had not adopted the seed plot technique) to compare to their present situation. The scenario assumed a 10% yield increase from adopting positive selection. This assumption of a 10% yield increase was based on multi-seasonal and multi-locational field data (Priegnitz et al., accepted) from the average percentage increase in 'yield per plant' of continually positive selected planted seed tubers compared to continually farmers' selected seed. Using a percentual increase instead of an absolute yield increase seems an appropriate choice; a percentual increase also gives variability in the outcome of the different farm types avoiding generalisation by using a fixed average yield increase.

First the net benefit was calculated from the original yield, by original labour costs, agricultural inputs and original gross benefits for the present situation. To determine the feasibility of investing in positive selection, positive seed selection was then added as an additional management practice with calculating i) the yield increase of 10% (and derived extra benefit), ii) extra investment costs of hired and family labour for positive selection (using data from the farms which are applying positive selection), and iii) 10% additional harvest costs due to the 10% yield increase. The *marginal rate of return* from positive selection (expressed in %) was calculated according to CIMMYT (1988) by the *change in net benefit* divided by the *change in costs*. Finally, the *adjusted net benefit* from investing in positive selection was calculated from the *adjusted gross benefit* in a new cost-benefit analysis and the new *rate of return* of potato production was calculated.

Statistical analysis

Differences between the farm types were assessed by one-way ANOVA and Welch test using SPSS, version 23.0. Mean separation was done using Fisher's protected LSD. Differences between types in percentage farms applying a practice were assessed with the Chi-square test, and mean separation was done with Bonferroni post-hoc test.

5.3. Results

Time, labour and costs involved in positive seed selection

Labour days and costs for positive selection were calculated for those farms that used positive selection in the four types (Table 5.2). Positive selection of one acre of potatoes took on average 1.2 days and was carried out using a total of 2.7 labour days, of which on average 1.5 days were hired labour and 1.2

days were family labour. These numbers did not differ significantly between farms from different types. Sixty-seven percent of the farms applying positive selection hired labour for this. Seventy-eight percent of the farms used family labour.

Also the costs of hired labour and family labour in applying positive selection were similar across the four FTs, with an average of 17,561 UGX (6.75 US Dollar) for hired labour and 14,922 UGX (5.74 US Dollar) for family labour per hectare (Table 5.2). The total labour costs per hectare were also similar across the different FTs with on average 32,482 UGX (12.49 US Dollar) per ha.

Investment in farm labour of positive selection

In Table 5.3 the investment in applying positive selection is presented as a percentage from the total labour costs of all other main agricultural management practices of each labour type on the farms applying positive selection. Comparing the labour costs of the other main agricultural practices to those of positive selection, it is clear that on average the 1st and 2nd land ploughing were requiring higher costs than carrying out all other management practices. Positive selection (Table 5.3) had much less costs than other main agricultural practices that these farms applied. The average investment of applying positive selection constituted 4.0% extra costs above the costs for the other practices on the farms applying positive selection; this percentage varied from 3.6% in FT 2 to 6.1% in FT 4 (Table 5.3).

Labour days and costs of other main agricultural management practices

To get a whole picture on the costs of positive selection compared to other practices, labour days and costs for the other main agricultural practices were calculated for both farm labour types. All other main agricultural management practices are here: 1st land ploughing, 2nd land ploughing, planting, spraying, weeding and harvesting.

A first land ploughing was applied by 230 out of 259 farms. The first land ploughing took on average 3.3 days per acre and a total labour input of 28.4 days, of which the majority was hired labour. The costs of hired labour

Table 5.2. Labour and costs of positive selection on farms in each Farm Type (FT) which adopted positive selection (PS) expressed in Ugandan shilling (UGX) (in parenthesis converted to US Dollar (USD)

	Mean (n=259)	Farm Type			
		FT 1 (n=104)	FT 2 (n=64)	FT 3 (n=38)	FT 4 (n=53)
Number of farms applying positive selection	72	2	40	21	10
Duration of positive selection in days per acre	1.2	1.5	1.3	1.1	1.1
Total labour days per positive selection per acre	2.7	4.0	2.7	2.6	3.0
Of which hired labour	1.5	2.0	1.5	1.4	1.6
Of which family labour	1.2	2.0	1.2	1.2	1.4
Hired labour					
Percentage (%) and absolute number (n in parenthesis) of farms using hired labour	67(48)	50(1)	77(31)	48(10)	60(6)
Number of hired labourers per acre	1.3	2.0	1.2	1.4	1.6
Cost per day per hired labourer in UGX (USD)	4891	5000	4896	4900	4833
	(1.88)	(1.92)	(1.88)	(1.88)	(1.86)
Costs hired labourers per acre in UGX (USD)	7110	10,000	6975	6810	7700
	(2.73)	(3.85)	(2.68)	(2.62)	(2.96)
Family labour					
Percentage (%) and absolute number (n in parenthesis) of farms using family labour	78(57)	100(2)	72(29)	86(18)	80(8)
Number of family labourers per acre	0.9	1.5	0.8	1.1	1.3
Cost per day per family labourer in UGX (USD)	4912	5000	4911	4944	4875
	(1.89)	(1.92)	(1.88)	(1.90)	(1.88)
Costs family labourers per acre in UGX (USD)	6041	10,000	5725	5909	6800
	(2.32)	(3.85)	(2.20)	(2.27)	(2.62)
Costs per ha for all farms using positive selection					
Average costs from hired labour per hectare in UGX (USD)	17,561	24,700	17,228	16,820	19,019
	(6.75)	(9.50)	(6.63)	(6.47)	(7.32)
Average costs from family labour per hectare in UGX (USD)	14,922	24,700	14,141	14,585	16,796
	(5.74)	(9.50)	(5.44)	(5.61)	(6.46)
Total labour costs positive selection per hectare in UGX (USD)	32,482	49,400	31,369	31,404	35,815
	(12.49)	(19.00)	(12.07)	(12.08)	(13.78)

Statistical analysis by one-way ANOVA ($p < 0.05$) did not show differences between types per hectare were on average 302,102 UGX (116.19 USD), and were lower in FT 4 compared to the other FTs. Total labour costs per ha were on average 380,545 UGX (146.36 USD), with lower costs in FT 4 compared to the other FTs.

A second land ploughing was applied by 249 out of 259 farms. The second land ploughing took on average 2.8 days per acre and a total labour input of 26.1 days, of which the majority was hired labour. Total labour costs per ha were on average 317,218 UGX (122.01 USD).

Planting took on average 1.8 days per acre and a total labour input of 13.5 days, with more hired labour days than family labour days. The labour input was higher in FT2 than in the other FTs. The number of hired labour days were also different in the FTs, with more hired labour days in FT 2 compared to FT 4. Total labour costs per ha were on average 169,490 UGX (65.19 USD).

Spraying (application of fungicides and/or pesticides) was applied by 237 out of 259 farms. Spraying took on average 2.5 days per acre and a total labour input of 7.7 days. Hired labour days for spraying was lower in FT 4 compared to FT 1 and FT 2; the same applied for the costs for hired labour. Total labour costs for spraying were on average 96,778 UGX (37.22 USD).

Weeding was applied by 251 out of 259 farms. Weeding took on average 2.3 days per acre and a total labour input of 15.1 days, with the highest number of labour days in FT 2. The number of hired labour days for weeding was highest in FT 2, and lowest in FT 4. Total labour costs were on average 184,240 UGX (70.86 USD).

Harvesting took on average 1.7 days per acre and a total labour input of 17.6 days, with more hired labour days compared to family labour days. Total labour costs per ha were on average 207,339 UGX (79.75 USD).

Fertilizer application was not included as a main agricultural practice, because farmers generally regarded that as part of the planting procedure. Organic input application was not considered in the analysis, as answers varied too much and could be hardly assessed (e.g. leaving cows in the field).

Table 5.3. Investment in farm labour (hired and family labour) of farms which adopted positive selection (PS), calculated from labour costs from all farm operations, and relative investment of labour in positive selection in the different Farm Types (FTs) expressed in Ugandan Shilling (UGX) (in parenthesis converted to US Dollar (USD))

	Mean (n=259)	Farm type			
		FT 1 (n=104)	FT 2 (n=64)	FT 3 (n=38)	FT 4 (n=53)
Number of farms adopting positive selection	73	2	40	21	10
Total hired labour costs in UGX (USD) per ha	1,187,328	627,380	1,539,610	848,149	708,149
	(456.66)	(241.30)	(592.16)	(326.21)	(272.37)
1st land ploughing	336,099	123,500	397,125	269,846	259,350
	(129.27)	(47.50)	(152.74)	(103.79)	(99.75)
2nd land ploughing	277,099	172,900	358,345	221,064	101,270
	(106.58)	(66.50)	(137.83)	(85.02)	(38.95)
Planting	177,196	209,950	233,772	89,038	140,790
	(68.15)	(80.75)	(89.91)	(34.25)	(54.15)
Spraying	79,925	24,700	95,940	55,822	77,629
	(30.74)	(9.50)	(36.90)	(21.47)	(29.86)
Weeding	164,064	74,100	230,035	88,802	89,414
	(63.10)	(28.50)	(88.48)	(34.15)	(34.39)
Positive selection	17,561	24,700	17,228	16,820	19,019
	(6.75)	(9.50)	(6.63)	(6.47)	(7.32)
Harvesting	169,351	59,280	207,870	132,792	121,771
	(65.14)	(22.80)	(79.95)	(51.07)	(46.84)
Total family labour costs in UGX (USD) per ha	315,624	290,225	303,459	351,563	291,460
	(121.39)	(111.63)	(116.72)	(135.22)	(112.10
1st land ploughing	74,302	0	65,585	91,760	118,560
	(28.58)	(0.00)	(25.23)	(35.29)	(45.60)
2nd land ploughing	68,560	37,050	68,120	86,450	40,755
	(26.37)	(14.25)	(26.20)	(33.25)	(15.68)
Planting	48,210	49,400	56,407	36,815	40,755
	(18.54)	(19.00)	(21.70)	(14.16)	(15.68)
Spraying	34,573	37,050	31,577	42,854	26,464
	(13.30)	(14.25)	(12.15)	(16.48)	(10.18)
Weeding	44,843	98,800	37,115	49,753	53,105
	(17.25)	(38.00)	(14.28)	(19.14)	(20.43)
Positive selection	14,922	24,700	14,141	14,585	16,796

	(5.74)	(9.50)	(5.44)	(5.61)	(6.46)
Harvesting	43,521	43,225	46,865	39,873	38,532
	(16.74)	(16.63)	(18.03)	(15.34)	(14.82)
Total costs hired and family labour including PS in UGX (USD) per ha	1,502,027	917,605	1,840,990	1,199,713	999,609
	(577.70)	(352.93)	(708.07)	(461.43)	(384.47)
Total costs hired and family labour without PS in UGX (USD) per ha	1,469,545	868,205	1,809,621	1,168,309	963,794
	(566.49)	(333.93)	(696,01)	(449.35)	(370.69)
Total labour costs positive selection per hectare as percentage of all other labour costs	4.0	5.4	3.6	3.6	6.1

Statistical analysis by one-way ANOVA ($p < 0.05$) did not show differences between types

Use of agricultural inputs and costs

On the farms where fertilizer was applied, the quantities per ha were highest in FT 1 and FT 2, and lowest in FT 3 and FT 4 (Supplementary Table 5.1). The fertilizer costs per ha were highest in FT 1 and FT 2, and lowest in FT 4, with FT 3 taking an intermediate position. Pesticides were not applied in FT 4, while the amount of pesticide input use was not significantly different for the other FTs (Supplementary Table S5.1); nevertheless, pesticide costs for the farms which applied pesticides were higher in FT 3 than in FT 1 and FT 2. Fungicide application varied also across farm types with the highest application rate in FT 1 and FT 2 and almost no application in FT 3; rates in FT 4 were not significantly different from FT 2 and FT3 (Supplementary Table S5.1). Fungicide cost per kg were lowest in FT 1. Costs for fungicide application were highest in FT 1 and FT 2 and very low in FT 3, where also only 2 farms used fungicides.

Revenue of non-adopting farms by investing in positive selection

Cost-benefit analysis of the present situation. In the cost-benefit analysis, first the present situation was calculated. Potato yield of non-adopters of positive selection was on average 9.9 Mg ha^{-1}, with highest yields in FT 2 with 14.2 Mg ha^{-1} and lowest in FT 4 with 7.9 Mg ha^{-1} (Table 5.4). The profitable yield was calculated from the present yield minus 1.5 Mg ha^{-1} and resulted on average in 8.4 Mg ha^{-1}, also with highest profitable yield in FT 2 with 12.7 Mg ha^{-1} and lowest in FT 4 with 6.4 Mg ha^{-1} (Table 5.4). The selling price per Mg was on average 691,595 UGX (266.00 USD) with lowest price in FT 4 with 634,615 UGX (244.08 US Dollar) per Mg and highest in FT 1 with 716,800 UGX (275,69 USD) per Mg (Table 5.4). As a result, the gross benefit was lowest in FT 4 and highest in FT 2.

Original total variable costs were on average 1,558,520 UGX (599.43 USD). Agricultural input costs were on average 301,395 UGX (115.92 USD), with higher fertilizer costs in FT 1 and FT 2, and higher pesticide costs in FT 1 and FT 3. While hired labour costs for all main agricultural practices did not differ significantly between farm types (with one exception for spraying.

The net benefit from without subtracting family labour was on average

4,648,827 UGX (1788.01 USD), with a lower net benefit in FT 4. Family labour costs did not vary and were on average 252,291 UGX (97.03 USD). The net benefit after subtracting opportunity costs were on average 4,396,536 UGX (1690.97 USD), with lowest net benefit in FT 4. The rate of return of potato production was on average 276% for the present situation.

Scenario with positive selection as an additional practice. In calculating the costs and benefits of uptake of positive selection in those farm households that had not adopted it, a benefit of a 10% yield increase was added to each farm in a type (Table 5.4). The extra yield increase varied between 0.8 and 1.4 Mg ha^{-1}. The extra income from a 10% yield increase was on average 691,595 UGX (266.00 USD) with the highest benefit in FT 1.

Additional to extra labour costs in doing positive selection (adopted from Table 5.2), a 10% increase in harvesting costs were added (adopted from harvest costs in this group). Total extra costs from positive selection with extra harvest costs were on average 52,746 UGX (20.28 USD) per ha.
The net benefit from investing in positive selection was on average 638,849 UGX (245.71 USD), the highest return for FT 2. The marginal rate of return of applying PS was on average 1211%, and varied from 755% in FT 4 to 1771% in FT 2.

Adjusted cost-benefit analysis. In the adjusted scenario with positive selection, the adjusted yield was on average 10.9 Mg ha^{-1} with highest yield FT 2 of 15.6 Mg ha^{-1} and lowest in FT 4 with 8.7 Mg ha^{-1} (Table 5.4). The adjusted profitable yield was on average 9.4 Mg ha^{-1} and also highest in FT 2 with a yield of 14.1 Mg ha^{-1} and lowest in FT 4 with 7.2 Mg ha^{-1} (Table 5.4). The gross field benefit followed the trend of yield level of the group of presently non-adopters in the different FTs. That means, the adjusted gross field benefit per hectare was on average 6,500,993 UGX (2500.38 USD) with lowest gross benefit in FT 4, and highest in FT 2.

Adjusted total costs from hired labourers and agricultural inputs were on average 1,341,202 UGX (515.84 USD) per ha with lowest costs in FT 4 and highest costs in FT 1 and FT 2. Total adjusted costs including family labourer was on average 1,593,493 UGX (612.88 USD) per ha and lowest in FT 4.

Table 5.4. Cost-benefit analysis of farms which have presently not adopted positive selection (PS) in the Farm Types (FT) before and after investing in positive selection (PS) with a 10% yield increase and the marginal net return of investing in positive selection expressed in Ugandan Shilling (UGX) (in parenthesis converted to US Dollar (USD))

	Mean(n=259)	Farm Type			
		FT 1(n=104)	FT 2 (n=64)	FT 3 (n=38)	FT 4 (n=53)
Number of farms not using PS	166	100	11	14	41
Cost-benefit analysis of present (original) situation					
Original Yield in Mg ha^{-1}	9.9	**10.7 b**	**14.2 c**	**9.1 ab**	**7.9 a**
Original Profitable yield in Mg ha^{-1}	8.4	**8.9 b**	**12.7 c**	**7.6 ab**	**6.4 a**
Selling price per Mg in UGX (USD)	691,595	**716,800 b**	**690,000 ab**	**671,429 ab**	**634,615 a**
	(266.00)	**(275.69)**	**(265.38)**	**(258.24)**	**(244.08)**
Original Gross field benefit in (UGX (USD) per ha	5,990,029	**6,654,167 bc**	**8,979,615 c**	**4,745,311 ab**	**3,984,404 a**
	(2303.86)	**(2559.30)**	**(3453.70)**	**(1825.12)**	**(1532.46)**
Original Total variable costs[2] in (UGX (USD) per ha	1,558,520	1,774,296	1,710,004	1,340,416	1,056,426
	(599.43)	(682.42)	(657.69)	(515.54)	(406.32)
Agricultural input costs in UGX (USD) per ha	301,395	**406,974 b**	**312,882 ab**	**78,246 a**	**116,451 a**
	(115.92)	**(156.53)**	**(120.34)**	**(30.09)**	**(44.79)**
Fertilizer costs	211,378	**283,433 b**	**244,755 b**	**45,166 a**	**83,438 a**
	(81.30)	**(109.01)**	**(94.14)**	**(17.37)**	**(32.09)**
Pesticide costs	22,525	**31,179 b**	**15,157 a**	**33,080 b**	**-**
	(8.66)	**(11.99)**	**(5.83)**	**(12.72)**	**(0.00)**
Fungicide costs	67,492	92,674	52,970	-	33,014
	(25.96)	(35.64)	(20.37)	(0.00)	(12.70)
Original Total costs from all hired labour in UGX (USD) per ha	1,039,807	1,122,446	1,076,920	1,000,526	744,474
	(399.92)	(431.71)	(414.20)	(384.82)	(286.34)
1st land ploughing	299,476	360,879	330,980	288,230	132,395
	(115.18)	(138.80)	(127.30)	(110.86)	(50.92)
2nd land ploughing	252,298	248,899	372,745	245,236	230,912
	(97.04)	(95.73)	(143.36)	(94.32)	(88.81)
Planting	116,175	135,115	102,393	137,614	63,018
	(44.68)	(51.97)	(39.38)	(52.93)	(24.24)
Spraying	64,727	**84,526 b**	**15,718 a**	**44,460 ab**	**30,596 a**
	(24.90)	**(32.51)**	**(6.05)**	**(17.10)**	**(11.77)**
Weeding	133,291	154,571	155,610	124,206	77,330
	(51.27)	(59.45)	(59.85)	(47.77)	(29.74)

Harvesting	173,840 (66.86)	156,432 (60.17)	175,617 (67.55)	181,369 (69.76)	213,200 (82.00)
Original Net benefits without subtracting opportunity costs in UGX (USD) per ha [3]	4,648,827 (1788.01)	**5,186,809 b** **(1994.93)**	**7,532,837 b** **(2897.25)**	**3,666,538 ab** **(1410.21)**	**3,119,848 a** **(1199.94)**
Original total costs from all family labour in UGX (USD)	252,291 (97.03)	256,387 (98.61)	320,202 (123.15)	261,644 (100.63)	195,501 (75.19)
1st land ploughing	70,039 (26.94)	65,992 (25.38)	190,190 (73.15)	54,150 (20.83)	55,681 (21.42)
2nd land ploughing	55,350 (21.29)	62,470 (24.03)	28,966 (11.14)	59,633 (22.94)	43,420 (16.70)
Planting	32,180 (12.38)	32,200 (12.38)	43,337 (16.67)	37,226 (14.32)	27,040 (10.40)
Spraying	24,294 (9.34)	23,285 (8.96)	28,966 (11.14)	28,052 (10.79)	24,063 (9.26)
Weeding	42,622 (16.39)	43,930 (16.90)	47,828 (18.40)	36,168 (13.91)	40,217 (15.47)
Harvesting	28,806 (11.08)	28,510 (10.97)	26,923 (10.36)	50,282 (19.34)	22,293 (8.57)
Original Net benefits including opportunity costs in UGX (USD) [4]	4,396,536 (1690.97)	**4,930,422 ab** **(1896.31)**	**7,269,611 b** **(2796.00)**	**3,404,895 ab** **(1309.58)**	**2,927,978 a** **(1126.14)**
Rate of return of potato farming in %[5]	276	**276**	**425**	**254**	**277**
Changes with positive selection					
Extra yield from positive selection in Mg ha^{-1} (10% of original yield)	1.0	**1.1 ab**	**1.4 b**	**0.9 a**	**0.8 a**
Extra benefit from 10% yield increase in UGX (USD) per ha	691,595 (266.00)	**788,480 ab** **(303.26)**	**966,000 b** **(371.54)**	**604,286 a** **(232.42)**	**507,692 a** **(195.26)**
Extra costs from carrying out PS in UGX (USD) [6] per ha	32,482 (12.49)	49,400 (19.00)	31,369 (12.07)	31,404 (12.08)	35,815 (13.78)
Extra harvesting costs (10% of original harvesting costs) in (UGX (USD) per ha	20,264 (7.79)	18,494 (7.11)	20,254 (7.79)	23,165 (8.91)	23,549 (9.06)
Total extra costs in (UGX (USD) per ha	52,746 (20.28)	67,894 (26.11)	51,623 (19.86)	54,570 (20.99)	59,364 (22.83)
Net benefit from investing in PS in UGX (USD) per ha [7]	638,849 (245.71)	**720,586 a** **(277.15)**	**914,377 b** **(351.68)**	**549,716 a** **(211.42)**	**448,328 a** **(172.43)**
Marginal rate of return from PS in %[8]	1211	1061	1771	1007	755
Adjusted cost-benefit analysis					

Adjusted yield with a 10% yield increase in Mg ha^{-1}	10.9	**11.8 b**	**15.6 c**	**10.0 ab**	**8.7 a**
Adjusted profitable yield Mg ha^{-1}	9.4	**10.3 b**	**14.1 c**	**8.5 ab**	**7.2 a**
Adjusted gross field benefit in UGX (USD) per ha	6,500,993 (2500.38)	**7,383,040 bc (2839.63)**	**9,945,615 c (3825.24)**	**5,282,454 ab (2031.71)**	**4,569,228 a (1757.39)**
Adjusted total costs from all hired labour and agricultural inputs in UGX[9] (USD) per ha	1,341,202 (515.84)	**1,597,314 b (614.35)**	**1,441,425 b (554.39)**	**1,133,342 ab (435.90)**	**920,289 a (252.95)**
Adjusted net benefit without subtracting opportunity costs in UGX (USD) per ha[3]	5,159,791 (1984.53)	**5,785,726 bc (2225.28)**	**8,504,190 c (3270.84)**	**4,149,112 ab (1595.81)**	**3,648,939 a (1403.43)**
Adjusted total costs from all hired and family labour plus agricultural inputs in UGX (USD) per ha[9]	1,593,493 (612.88)	**1,853,701 b (712.96)**	**1,761,627 b (677.55)**	**1,394,986 ab (536.53)**	**1,115,790 a (429.15)**
Adjusted net benefit including opportunity costs in UGX (USD) per ha[4]	4,907,500 (1887.50)	**5,529,339 bc (2126.66)**	**8,183,988 c (3147.68)**	**3,887,468 ab (1495.18)**	**3,453,438 a (1328.24)**
Adjusted rate of return for potato farming in % [5]	298	**298**	**464**	**278**	**309**

[1] profitable yield was calculated from the total yield minus a seed rate of 1.5 Mg ha^{-1} for planting the next crop
[2] all variable costs were derived from hired labour, family labour and agricultural input costs
[3] net benefit was calculated in this row from hired labour costs and agricultural inputs without opportunity costs
[4] net benefit was calculated in this row from hired and family labour costs and agricultural inputs
[5] rate of return was calculated by net benefit from all labour costs and agricultural input costs divided by all variable costs, multiplied by 100
[6] extra costs for PS were derived from the investment costs in PS of hired and family labour as presented in Table 5.2.
[7] net benefit was calculated from the extra benefit of a 10% yield increase minus the total extra costs from investing in PS
[8] marginal rate of return was calculated from the net benefit of investing in PS divided by extra costs a farmer would spend, multiplied by 100
[9] costs are referring here to 1st land ploughing, 2nd land ploughing, planting, weeding, spraying, positive selection and harvesting
Statistical analysis was derived from one-way ANOVA with Welch Test; where $p < 0.05$ was significant the mean separation was set in **bold**

The adjusted net benefit without subtracting opportunity costs was on average 5,159,791 UGX (1984.53 USD) and was lowest in FT 4 and highest in FT 2. The adjusted net benefit per ha including subtracting opportunity costs was on average 4,907,500 UGX (1887.50 USD), with highest net benefit in FT 2. The adjusted rate of return for potato production including positive selection was on average 298%, with a higher return in FT 2.

5.4. Discussion

The aim of this research was to assess the time, labour and costs of positive selection invested by farmers that already apply this seed selection method. Further, this research compared these costs and labour data to those of other main agricultural practices and explored with a cost-benefit analysis if it is economically feasible for non-adopters of positive selection to invest in this technique to achieve a higher potato yield. To our knowledge, this detailed analysis regarding labour days, labour requirements and costs for different practices was not carried out before.

Time, labour and costs required in applying positive selection. Positive selection on average took 1.2 days per acre and was carried out in a total of 2.7 labour days (Table 5.2). Labour was either in the form of hired labour, family labour or a combination of both labour types. Positive selection required the smallest quantity of labour days (2.7 labour days per acre) compared with other main agricultural practices: 1st land ploughing (28.4 labour days per acre), 2nd land ploughing (26.1 labour days per acre), planting (13.5 labour days per acre), spraying (7.7 labour days per acre), weeding (15.1 labour days per acre), and harvesting (17.6 labour days per acre) (Supplementary Table S5.2). All practices were carried out with manual labour. Farms from different FTs did not differ in their labour costs for positive selection and other main agricultural practices, nor were total costs significantly different across the four FTs (Table 5.3). On these farms applying positive selection, the average total labour costs including the positive selection were 1,502,027 UGX (577,70 USD) (Table 5.3). In our study, an average investment of 4.0% extra labour costs for applying positive selection was made, which is a small share and an acceptable investment when compared with other main agricultural costs (Table 5.3).

Scenario for non-adopters to adopt in positive selection

Cost-benefit analysis of the present situation. Cost-benefit analysis of the present situation of non-adopters of positive selection showed that the current rate of return in potato production was on average 276%; this shows that potato production is an economically feasible business (Table 5.4) (Bonabana-Wabbi et al., 2013). However, only the variable costs were taken into account in this analysis. Including fixed costs in the analysis might have led to a different outcome; Feder et al. (1982) observed that in small farms high fixed costs are reducing the intention to adopt new technologies.

Cost-benefit analysis of the adjusted situation. A predicted 10% yield increase was chosen as a realistic increase in crop productivity across different potato varieties and farm locations (Priegnitz et al., submitted). The adjusted 10% yield increase ranged between 0.8 and 1.4 Mg ha^{-1} resulting in an extra gross benefit of an average of 691,595 UGX (266.00 USD) per ha. Extra costs were on average 52,746 UGX (20.28 USD) per ha and consisted of costs for applying positive selection (32,482 UGX (12.49 USD) per ha; Table 5.2) and 10% extra harvests costs (20,264 UGX (7.79 USD) per ha; Table 5.4). The net benefit from investing in positive selection was on average 638,849 UGX (245.71 USD) per ha and was highest in FT 2 due to a higher extra yield. The resulting marginal rate of return of PS for all FTs was much higher than 100% with an average of 1211%; CIMMYT (1988) suggested that a minimum of 100% marginal rate of return is necessary for making a positive decision in the adoption of a new technique. It should be noted though, that the revenue of positive selection is only achieved at least one cropping season later and not immediately. In showing that adopting positive selection is an economical wise decision, some farmers might still do not adopt positive selection. Smallholder farmers are making sensible decisions when investing cash in potato farming, because of insecure markets, drought and diseases (Gildemacher et al., 2009). Michalscheck et al. (2018) stated that affordability of certain agricultural inputs and labour investment might be more an obstacle for farms that are less resourceful regarding cash availability than for farms that are more resourceful; this may hold for FT 4. Also, competition of labour demand and limited labour availability is of importance and might hinder the improvement of management practices (Silva et al., 2019).

This research shows that some farmers may realise more benefits than others. However, this study confirms the estimated calculations by Gildemacher et al. (2011); and shows that in all types positive selection can increase benefits for farmers because positive selection can improve yield compared to farmers' selection (Gildemacher et al., 2011; Schulte-Geldermann et al., 2012) and shows that costs can be more than compensated in each type even if a 10% yield increase is realised.

Implications

Positive selection requires additional hired and/or family labour days and therefore cash investment, but relatively little when compared with other main agricultural practices. Farmers might even gain an extra income by selling positive selected seed tubers. With a high marginal rate of return, it is profitable to invest in positive selection, as it helps to slow down the degeneration process in seed potatoes, to maintain seed potato quality and to increase yield compared to farmers' selection. The results show that positive seed selection can be a valuable option for cost effective seed potato production management in the informal seed sector in Uganda. Based on the results of this research, extension personnel and farmers can assess more accurately that investing in positive selection is a wise decision.

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Supplementary materials

Table S5.1. Amount and costs of agricultural inputs[1,2] for potato production used by adopters of these technologies in different farm types. Data are in Ugandan Shilling (UGX) (in parenthesis in US Dollars (USD) and/or per hectare.

Input per ha	Mean (n=259)	Farm Types			
		FT 1 (n=104)	FT 2 (n=64)	FT 3 (n=38)	FT 4 (n=53)
Fertilizer quantification[3]					
Fertilizer amount (kg)	137.1	**190.5 b**	**166.5 b**	**61.9 a**	**50.6 a**
per ha	(n=142)	(n=66[2])	(n=37[2])	(n=16[2])	(n=23[2])
Fertilizer cost per kg	2,740	2,630	2,908	2,293	3,027
in UGS (USD)	(1.05)	(1.01)	(1.12)	(0.88)	(1.16)
	(n=138)	(n= 64)	(n=37)	(n=15)	(n=22)
	227,016	**289,631 c**	**279,805 bc**	**131,918 ab**	**108,587 a**
Fertilizer costs per ha	(87.31)	(111.39)	(107.62)	(50.74)	(41.76)
in UGS (USD)	(n=138)	(n= 64)	(n=37)	(n=15)	(n=22)
Pesticide quantification[3]					
Pesticides amount (l)	2.8	3.1	2.1	3.3	-
per ha	(n=172)	(n=93[2])	(n=47[2])	(n=32[2])	(n=0)
Pesticide cost per l in	12,734	12,154	12,319	14,997	-
UDX (USD)	(4.90)	(4.67)	(4.74)	(5.77)	(n=0)
	(n=172)	(n=93)	(n=47)	(n=32)	
Pesticide costs per ha	39,168	**34,637 a**	**34,681 a**	**58,876 b**	-
in UGX (USD)	(15.06)	(13.32)	(13.33)	(22.64)	(n=0)
	(n=172)	(n=93)	(n=47)	(n=32)	
Fungicide quantification[3]					
Fungicide amount (kg)	9.1	**12.7 c**	**11.1 bc**	**0.5 a**	**6.0 ab**
per ha	(n=178)	(n=86[2])	(n=61[2])	(n=2[2])	(n=29[2])
Fungicide cost per kg	10,803	**9070 a**	**12,412 b**	**12,000 ab**	**12,912 b**
in UGX (USD)	(4.15)	(3.48)	(4.77)	(4.61)	(4.96)
	(n=177)	(n=86)	(n=60)	(n=2)	(n=29)
Fungicide costs per ha	70,496	**95,215 b**	**92,601 b**	**5,460 a**	**43,901 ab**
in UGX (USD)	(27.11)	(36.62)	(35.62)	(2.10)	(16.88)
	(n=177)	(n=86)	(n=60)	(n=2)	(n=29)
Agricultural input	321,142	**412,970 b**	**399,023 b**	**173,881 a**	**152,488 a**
costs[4] per ha per	(123.52)	(158.83)	(153.47)	(66.87)	(58.65)
season in UGX (USD)	(n=227)	(n=101)	(n=59)	(n=34)	(n=33)

[1] Information on units was collected from the farm households on 1-acre basis and recalculated to 1 ha

[2] Storage input costs were not included as units varied too much

[3] Number of farms from which it was possible to quantify the use based on the information provided

[4] The total was calculated from each cost which a farm household applies, i.e. if a farm was only using one input the total was derived from one input

Statistical analysis was derived from one-way ANOVA and Welch Test; where $p < 0.05$ was significant the mean separation was set in **bold**

Table S5.2. Duration of operation, labour requirements (hired labour and family labour), number of working days and costs per acre per completed management practice from farms in each Farm Type (FT) expressed in Ugandan Shilling (UGX) and recalculated per hectare (in parenthesis converted to US Dollar (USD)

Management practice	Mean (n=259)	Farm Type			
		FT 1 (n=104)	FT 2 (n=64)	FT 3 (n=38)	FT 4 (n=53)
First land ploughing[1]					
Number of farms applying 1st land ploughing	230	95	55	36	44
Duration of 1st land ploughing in days per acre	3.3	3.4	3.3	3.7	2.7
Labour days per 1st land ploughing per acre	28.4	29.8	32.7	30.0	18.5
of which hired labour	22.7	**24.3b**	**26.9b**	**23.5b**	**13.2a**
of which family labour	5.7	5.5	5.8	6.5	5.3
Hired labour					
Percentage (%) and absolute number (n in brackets) of farms using hired labour	88.7 (205)	89.6 (86)	94.6 (52)	88.9 (32)	79.5 (35)
Number of hired labourers per acre	7.5	**7.9 b**	**8.8 b**	**8.0 b**	**4.3 a**
Cost per day per hired labourer in UGX (USD)	5002 (1.92)	5224 (2.01)	5129 (1.97)	4635 (1.78)	4588 (1.76)
Costs hired labourers per acre in UGX (USD)	121,781 (46.84)	**142,685 b** (54.88)	**142,009 b** (54.62)	**109,777 b** (42.22)	**60,251 a** (23.17)
Family labour					
Percentage (%) and absolute number (n in brackets) of farms using family labour	69.4 (161)	**58.3 a** (56)	**66.1 a** (37)	**75.0 ab** (27)	**93.2 b** (41)
Number of family labourers per acre	1.6	1.4	1.5	1.7	1.9
Cost per day per family labourer in UGX (USD)	5167 (1.99)	4964 (1.91)	6216 (2.39)	4777 (1.84)	4756 (1.83)
Costs family labourers per acre in UGX (USD)	30,557 (11.75)	27,137 (10.44)	39,436 (15.17)	31,556 (12.14)	26,023 (10.01)
Results per ha					
Costs hired labour per hectare in UGX (USD)	302,102 (116.19)	**352,432 b (135.55)**	**350,762 b (134.91)**	**271,150 b (104.29)**	**152,280 a (58.57)**

Costs family labour per hectare in UGX (USD)	74,804	67,028	97,408	77,942	65,771
	(28.77)	(25.78)	(37.46)	(29.98)	(25.30)
Total labour costs[2] 1st land ploughing per hectare in UGX	380,545	**423,170 b**	**454,547 b**	**349,093 b**	**218,051 a**
(USD)	(146.36)	**(162.76)**	**(174.83)**	**(134.27)**	**(83.87)**
Second land ploughing[1]					
Number of farms applying 2nd land ploughing	249	101	62	36	50
Duration of 2nd land ploughing in days per acre	2.8	2.6	3.2	2.8	2.5
Total labour days per acre	26.1	25.3	32.7	24.7	20.3
Of which hired labour	21.4	20.7	27.8	18.9	16.7
Of which family labour	4.7	4.6	4.9	5.8	3.6
Hired labour					
Percentage (%) and absolute numbers (n in brackets) of	89.9	89.0	93.5	91.6	86.0
farms using hired labour	(223)	(89)	(58)	(33)	(43)
Number of hired labourers per acre	7.9	**8.3 b**	**9.4 b**	**7.7 ab**	**5.3 a**
Cost per day per hired labourer in UGX (USD)	5167	4964	6216	4777	4746
	(1.98)	(1.91)	(2.39)	(1.84)	(1.82)
Costs hired labourers in UGX (USD)	104,032	98,738	138,435	90,883	81,000
	(40.01)	(37.98)	(53.24)	(34.96)	(31.15)
Family labour					
Percentage (%) and absolute numbers (n in brackets) of	66.7	**57.4 a**	**64.5 a**	**72.7 ab**	**84.0 b**
farms using family labour	(167)	(59)	(40)	(26)	(42)
Number of family labourers per acre	1.5	1.5	1.3	1.8	1.6
Cost per day per family labourer in UGX (USD)	4976	4933	5207	4752	4922
	(1.91)	(1.90)	(2.00)	(1.83)	(1.89)
Costs family labourers per acre in UGX (USD)	24,298	25,780	24,790	29,111	17,260
	(9.35)	(9.92)	(9.53)	(11.20)	(6.64)
Results per ha					
Average costs from hired labour per hectare in UGX	256,958	243,883	341,936	224,358	200,070
(USD)	(98.83)	(93.80)	(131.51)	(86.29)	(76.95)
Average costs from family labour per hectare in UGX	60,017	63,677	61,232	71,904	42,632
(USD)	(23.08)	(24.49)	(23.55)	(27.66)	(16.40)

Total labour costs[2] 2nd land ploughing per hectare in UGX (USD)	317,218 (122.01)	307,559 (118.29)	403,168 (155.06)	296,262 (113.95)	243,572 (93.68)
Planting[3]					
Number of farms applying planting	250	100	62	38	50
Duration of planting in days per acre	1.8	1.9	1.9	1.8	1.7
Labour days per planting per acre	13.5	**12.7 a**	**19.4 b**	**11.9 a**	**9.1 a**
Of which hired labour	10.4	**9.9 ab**	**15.2 b**	**8.8 ab**	**6.5 a**
Of which family labour	3.1	2.8	4.2	3.1	2.6
Hired labour					
Percentage (%) and absolute numbers (n in brackets) of farms using hired labour	83.2 (206)	85.0 (86)	83.8 (56)	86.8 (32)	76.0 (35)
Number of hired labourers per acre	5.1	**5.0 ab**	**6.6 b**	**4.7 ab**	**3.8 a**
Cost per day per hired labourer in UGX (USD)	5058 (1.94)	5273 (2.02)	4919 (1.89)	4818 (1.85)	4972 (1.91)
Costs hired labourers in UGX (USD)	53,357	54,284	74,556	3,316	32,429
Family labour					
Percentage (%) and absolute numbers (n in brackets) of farms using family labour	75.8 (192)	67.6 (69)	77.4 (48)	84.2 (32)	84.3 (43)
Number of family labourers per acre	1.7	1.5	1.9	1.7	1.6
Cost per day per family labourer in UGX (US Dollars)	4882 (1.87)	4920 (1.89)	4872 (1.87)	4906 (1.88)	4813 (1.85)
Costs family labourers per acre in UGX (US Dollars)	15,201 (5.85)	13,335 (5.13)	20,577 (7.91)	15,000 (5.77)	12,420 (4.78)
Results per ha					
Average costs from hired labour per hectare in UGX (USD)	131,792 (50.69)	134,083 (51.57)	184,154 (70.83)	106,990 (41.15)	80,099 (30.81)
Average costs from family labour per hectare in UGX (USD)	37,547 (14.44)	32,937 (12.67)	50,826 (19.55)	37,050 (14.25)	30,677 (11.80)
Total labour costs[2] planting per hectare in UGX (USD)	169,490 (65.19)	167,020 (64.24)	234,981 (90.38)	144,040 (55.40)	111,402 (42.85)
Spraying[4]					
Number of farms applying spraying	237	100	61	37	39
Duration of spraying in days per acre	2.5	2.6	2.8	2.3	1.9

Labour days per spraying per acre	7.7	8.5	8.9	6.7	5.1
Of which hired labour	5.5	**6.6 b**	**6.4 b**	**3.9 ab**	**3.1 a**
Of which family labour	2.2	1.9	2.5	2.7	1.9
Hired labour					
Percentage (%) and absolute numbers (n in brackets) of farms using hired labour	89.9 (185)	89.0 (84)	93.5 (50)	91.6 (26)	86.0 (25)
Number of hired labourers per acre	2.6	2.8	2.5	2.6	2.3
Cost per day per hired labourer in UGX (USD)	5007 (1.92)	5028 (1.93)	4940 (1.90)	5076 (1.95)	5000 (1.92)
Costs hired labourers in UGX (USD)	28,174 (10.84)	**33,444 b (12.86)**	**32,475 b (12.49)**	**20,216 ab (7.78)**	**15,615 a (6.01)**
Family labour					
Percentage (%) and absolute numbers (n in brackets) of farms using family labour	59.9 (146)	49.0 (49)	62.9 (39)	73.7 (28)	75.0 (30)
Number of family labourers per acre	1.5	1.5	1.4	1.6	1.4
Cost per day per family labourer in UGX (US Dollars)	4954 (1.90)	4979 (1.91)	4805 (1.85)	5107 (1.96)	4965 (1.91)
Costs family labourers per acre in UGX (US Dollars)	10,961 (4.22)	9,650 (3.71)	11,784 (4.53)	14,378 (5.53)	9,795 (3.77)
Results per ha					
Average costs from hired labour per hectare in UGX (USD)	69,589 (26.77)	**82,608 b (31.77)**	**80,214 b (30.85)**	**49,934 ab (19.21)**	**38,570 a (14.83)**
Average costs from family labour per hectare in UGX (USD)	27,074 (17.63)	23,836 (19.93)	29,106 (17.97)	35,515 (18.72)	24,193 (12.51)
Total labour costs[2] spraying per hectare in UGX (USD)	96,778 (37.22)	106,884 (41.11)	109,320 (42.05)	85,449 (32.87)	62,763 (24.14)
Weeding[5]					
Number of farms applying weeding	251	101	61	38	51
Duration of weeding in days per acre	2.3	2.2	2.4	2.4	2.1
Total labour days per weeding per acre	15.1	**15.1 ab**	**20.3 b**	**13. 2a**	**10.4 a**
Of which hired labour	11.5	**11.6 b**	**16.5 c**	**9.4 ab**	**6.7 a**
Of which family labour	3.6	3.5	3.8	3.8	3.7

Hired labour					
Percentage (%) and absolute numbers (n in brackets) of	86.5	86.1	96.7	84.2	76.5
farms using hired labour	(218)	(87)	(60)	(32)	(39)
Number of hired labourers per acre	5.1	**5.2 bc**	**6.7 c**	**3.9 ab**	**3.5 a**
Cost per day per hired labourer in UGX (USD)	5044	5430	4754	4741	4868
	(1.94)	(2.08)	(1.83)	(1.82)	(1.87)
Costs hired labourers per acre in UGX (USD)	56,805	**60,695 bc**	**79,541 c**	**42,711 ab**	**32,412 a**
	(21,85)	**(23,34)**	**(30,59)**	**(16,43)**	**(12,47)**
Family labour					
Percentage (%) and absolute numbers (n in brackets) of	70.2	66.6	65.6	78.9	76.5
farms using family labour	(178)	(69)	(40)	(30)	(39)
Number of family labourers per acre	1.5	1.5	1.4	1.6	1.4
Cost per day per family labourer in UGX (USD)	5064	5311	4825	5000	4923
	(1.95)	(2.04)	(1.83)	(1.92)	(1.89)
Costs family labourers per acre in UGX (USD)	17,786	18,428	16,705	18,263	17,451
	(6.84)	(7.09)	(6.43)	(7.02)	(6.71)
Results per ha					
Average costs from hired labour per hectare in UGX	140,310	**149,916 bc**	**196,466 c**	**105,495 ab**	**80,057 a**
(USD)	(53.97)	**(57.66)**	**(75.56)**	**(40.58)**	**(30.79)**
Average costs from family labour per hectare in UGX	43,931	45,516	41,261	45,110	43,104
(USD)	(16.90)	(17.51)	(15.87)	(17.35)	(16.58)
Total labour costs[2] weeding per hectare in UGX (USD)	184,240	**195,433 bc**	**237,727 c**	**150,605 ab**	**123,161 a**
	(70.86)	**(75.17)**	**(91.43)**	**(57.93)**	**(47.37)**
Harvesting[3]					
Number of farms harvesting	249	99	61	38	51
Duration of harvesting in days per acre	1.7	1.7	1.8	1.8	1.4
Total labour days per operation per acre	17.6	19.3	20.3	16.9	11.8
Of which hired labour	14.0	14.8	16.9	13.2	9.7
Of which family labour	3.6	**4.5 b**	**3.4 b**	**3.7 b**	**2.1 a**
Hired labour					
Percentage (%) and absolute numbers (n in brackets) of	93.6	92.9	96.7	89.5	94.1
farms using hired labour	(233)	(92)	(59)	(34)	(48)
Number of hired labourers per acre	7.9	7.6	9.5	7.8	6.7
Cost per day per hired labourer in UGX (USD)	5151	4773	4887	4735	6510
	(1.98)	(1.84)	(1.88)	(1.82)	(2.50)

Costs hired labourers per acre in UGX (USD)	70,232 (27.01)	61,742 (23.75)	82,361 (31.68)	62,658 (24.10)	77,660 (29.87)
Family labour					
Percentage (%) and absolute numbers (n in brackets) of farms using family labour	69.8 (175)	**60.6 a** (61)	**63.9 a** (39)	**84.2 b** (32)	**84.3 b** (43)
Number of family labourers per acre	2.4	2.9	2.3	2.5	1.9
Cost per day per family labourer in UGX (USD)	4925 (1.89)	4950 (1.90)	4897 (1.88)	4906 (1.88)	4930 (1.89)
Costs family labourers per acre in UGX (USD)	13,601 (5.23)	11,939 (4.59)	15,984 (6.15)	18,158 (6.98)	10,549 (4.06)
Results per ha					
Average costs from hired labour per hectare in UGX (USD)	173,472 (66.72)	152,503 (58.66)	203,431 (78.24)	154,765 (59.53)	191,820 (73.78)
Average costs from family labour per hectare in UGX (USD)	33,594 (12.92)	29,489 (11.34)	39,480 (15.18)	44,850 (17.25)	26,056 (10.02)
Total labour costs[2] harvesting per hectare in UGX (USD)	207,339 (79,75)	182,295 (70,11)	242,910 (93.43)	199,615 (76.78)	218,397 (84.00)

[1] some farms practise only one ploughing, that is why a higher number of farms is represented in 2[nd] land ploughing
[2] total labour costs per practice was derived from the farms which are using the practice either with hired and/or family labour and were willing to share the information
[3] sorting potatoes is done with planting and harvesting; at planting fertilizer is applied
[4] spraying was derived from how many times a farmer is spraying and how many days it takes until one full spraying is complete (i.e. variation was between 'no spraying' to '10 times = 10 days' spraying per season and per acre)
[5] weeding was derived from how many times a farmer is weeding and how many days it takes until one full weeding is complete (i.e. variation was between 'no weeding' to '9 times=9 days' weeding per season and per acre); weeding does also include hilling up
Statistical analysis was derived from one-way ANOVA and Welch Test, were $p < 0.05$ was significant the mean separation was set in **bold**

CHAPTER 6

General discussion

6.1 Introduction

In Uganda and most of the African countries, potato is an important food and cash crop. With a growing population, rising demand across the country and limited land availability yield needs to be improved to sustain food, nutrition and cash security. With an attainable yield of 25 Mg ha^{-1} (International Potato Center, 2011), potato yield in Uganda is less than 5 Mg ha^{-1}. Chapter 1 of this thesis mentions the non-availability of good quality seed as the most yield constraining factor, because Uganda does not have a well-functioning formal seed system yet. It relies on the informal seed sector where seed tubers are highly degenerated by viruses and other seed-borne pathogens; commonly, the seed tubers used are self-produced tubers saved from the former harvest, supply from neighbours or seed bought on the local market (Gildemacher et al., 2009; McGuire and Sperling, 2016). In crop production, seed is the most crucial and important type of input (Louwaars and de Boef, 2012) and seed degeneration is a challenge for many potato smallholder farmers in the world (Thomas-Sharma et al., 2016). In order to increase potato yield in Uganda and reverse the problem of seed degeneration, it was stated in Chapter 1 that one solution could lie in the adoption of the seed management practice of positive selection to innovate the smallholder production system.

This thesis reports on key research findings to understand positive selection. They focus on the virological and agronomical aspects of applying positive selection to reduce degeneration and stimulate a regeneration. The adoption of positive selection by smallholder farmers was evaluated and its economic feasibility was assessed. The following specific research objectives were addressed in this research:

i) To analyse agronomic, social, and socio-economic characteristics of the potato producing farm types in southwestern Uganda differing in the adoption of innovative production practices, including positive selection (Chapter 2);

ii) To quantify effects of positive selection across multiple generations on incidence of different viruses in the seed potato tubers (Chapter 3) and how this affects tuber yield and yield components (Chapter 4);

iii) To evaluate costs and benefits of positive selection in order to assess its feasibility and affordability for different types of small-scale farmers (Chapter 5).

This final chapter broadens the discussion of the afore research chapters in understanding positive selection with the overall goal of improving the availability and production of healthy seed potatoes for smallholder farmers in southwestern Uganda by reducing degeneration caused by viruses, by stimulating the regeneration of own produced seed, and by evaluating the adoption and applicability of positive selection in seed production and to compare positive selection with the current practice of farmers' seed selection from the tuber harvest. Findings will be discussed from an interdisciplinary point of view and sections are presented as follows: (1) Key findings of this research in view of the research objectives, (2) Progress in understanding positive selection, (3) Outlook on linking the integrated seed sector approach with the integrated seed health strategy, (4) Limitations of the study, and (5) Concluding remarks on results.

6.2 Key findings of this research in view of the research objectives

i) To analyse agronomic, social, and socio-economic characteristics of the potato producing farm types in southwestern Uganda differing in the adoption of innovative production practices, including positive selection (Chapter 2)

Chapter 2 showed two complementary parts regarding the adoption of innovative management practices. Innovative management practices were defined as improved practices like uptake of fertilizer, organic input, fungicide input, pesticide input, the use of either seed plot technique (SPT) and/or positive selection (PS), the use of formal quality seed from Kachwekano Zonal Agriculture and Research Development Institute (KAZARDI) or Ugandan National Seed Potato Producers Association (UNSPPA), and the use of sole cropping. A semi-structured questionnaire was used to collect detailed information from smallholder potato farmers in the southwestern region of Uganda. Then the collected data were analysed using Principal Component Analysis (PCA) and Cluster Analysis (CA) to identify homogeneous clusters of farms differing in uptake of innovative management practices and in farm type (typology).

The clusters revealed four different farm types with different adoption rates: highly innovative farms (FT 2), innovative farms (FT 1), semi-innovative farms (FT 3), and low innovative farms (FT 4). The innovation package of highly innovative farms (FT 2) with relatively frequent use of organic input, fungicide input, pesticide input, SPT and/or PS, quality declared seed and sole cropping was associated with the highest yield; the innovation package of low innovative farms (FT 4) with relatively frequent use of fungicides and no use of pesticides was associated with lowest yield. In our case, a higher adoption of innovation practices was associated with a higher potato yield and more income, and more access to extension services and knowledge; those farmers possessed more land and hired more labour. Our findings are consistent with previous studies like those of Ortiz et al. (2013) and Okoboi et al. (2014) that extension service plays a vital role in adoption of innovations and therefore productivity. Additionally, our results also are in line with the findings of Tadesse et al. (2017) that social circumstances like labour, land and cash determine the adoption process.

ii) To quantify effects of positive selection across multiple generations on incidence of different viruses in the seed potato tubers (Chapter 3)

For the second objective, multi-seasonal field trials in different locations with five different seed lots and applying different seed selection practices were carried out in southwestern Uganda. Six potato viruses were considered (PLRV, PVX, PVY, PVA, PVS, and PVM) that differ in the severity of symptoms and mode of transmission.

Positive selection could clearly keep the incidence of viruses at a reduced level, compared to farmers' selection, but our results on virus reduction were less strong than expected based on results from Gildemacher et al. (2011) and Schulte-Geldermann et al. (2012). Less strong results were partly due to the limited severity of visual symptoms of the different viruses in the potato plant, to the initial high virus incidence in the starting material and the high risk for primary infection. Additionally, experimental conditions led to a low selection pressure within the plot (selection of many plants) which differentiated these findings from those by Gildemacher et al. (2011) and Schulte-Geldermann et al. (2012).

In positive-selected seed compared to farmers' selected seed a reduction of PLRV and PVX, viruses that commonly display clear visual symptoms, was possible. PVY and PVA, which show mild visual symptoms, were maintained at low levels. PVS and PVM are poorly visible and because of an initial high incidence in all seed lots of cv. Victoria in all experiments it was not possible to reduce virus infection levels significantly in those seed lots. In cv. Katchpot 1, the initial level for PVS and PVM was maintained. In cv. Rwangume a significant decrease in PVS was found at the end of the field experiments in all seed selection treatments. Either cv. Rwangume is resistant to PVS or - like Bertschinger et al. (2017) described - incomplete autoinfection contributes to a lower virus incidence in this cultivar. Incomplete autoinfection occurs when not all daughter tubers become systemically infected from an infected mother plant. Cv. Rwangume produced more tubers and smaller tubers than the other cultivars used; a higher selection pressure could have increased the health status further. Positive selection can enhance the regeneration of a degenerated seed stock in cv. Rwangume. For cv. Victoria and Katchpot 1, a decrease in selected viruses like PLRV and PVX is possible by applying positive selection, but this only applies if virus incidence at plot level is at intermediate levels. Our findings are in line with Schulte-Geldermann et al. (2012) that different potato cultivars differ in their response to tested viruses. Positive selection is a technique in the innovative seed system management for i) combating viruses with clear visual symptoms in keeping the virus level at lower levels compared to farmers' selected seed, and ii) positive selection can help to maintain seed quality if no 100% or almost fully infected plants in the potato crop occur.

iii) To quantify effects of positive selection across multiple generations on tuber yield and yield components (Chapter 4)

The third research objective analysed yield and yield components in multi-seasonal experiments in different locations, when applying different seed selection practices.

Results of the experiments showed that 1) tuber yield per plant (kg) was always higher in the continuous positive-selected seed treatment when compared to the continuous farmers' selected seed, 2) an overall 10% yield increase (kg/plant) could be achieved across all seed lots, seasons and locations and 3) within a plot, the positive-selected plants were producing significantly more tubers compared to non-selected plants, which makes the plant selection process more efficient. One experiment (Experiment 2, Table 4.5) was similar in the results of Gildemacher et al. (2011) and Schulte-Geldermann et al. (2012) with a yield increase of 22% in subsequent seasons when positive-selected seed was planted compared to continuously planting farmer-selected seed. It can be justified that positive selection is a reliable option to keep yield at a higher level than farmers' selection when it is applied continuously. However, our experimental results also showed high fluctuations in yield, a phenomenon that was also observed by Ronner (2018) and van Vugt (2018).

iv) To evaluate costs and benefits of positive selection in order to assess its feasibility and affordability for different types of small-scale farmers (Chapter 5)

The fourth research objective was to assess time, labour and costs of positive selection invested by farmers who carry out positive selection, to compare these costs and labour data to those of other practices and to explore if it is economically feasible for non-adopters of positive selection to invest in this technique to achieve a higher crop yield. All the data was obtained from the smallholder survey and the typology which was constructed in Chapter 2 and the overall yield benefit obtained from Chapter 4.

Results showed that an investment rate of only between 3.6 and 6.1% of additional labour is needed (Table 5.3) to achieve an additional potato yield of 0.7 to 1.4 Mg ha^{-1} (Table 5.4). The marginal rate of return of positive selection varied between 755 and 1771% and was superior to the acceptable 100% (CIMMYT, 1988) in all farm types. The hindrance in adopting positive selection might be in inadequate training about the seed innovation management, in not seeing immediate benefits, plus it requires additional labour and costs. Farmers therefore may only use minimum labour requirements and might not be willing to spend additional labour input (Tadesse et al., 2017; Michalscheck et al., 2018). Additionally, labour competition may also hinder the adoption of positive selection (McCullough, 2017; Silva et al., 2019).

6.3. Progress in understanding positive selection

This section reflects on key issues drawn from the research findings. First, results from the field experiments will be discussed and, second, results on the adoption and the economic benefit of positive selection will be presented.

Insights on virus incidence and yield components from field experiments

Positive selection involves selecting potato plants based on absence of visual disease symptoms and the best-looking plants in the potato plot are chosen for the next generation. With this technique a slower degeneration rate of the seed tubers and a regeneration of a potato crop are aimed at.

The findings described in Chapter 3 confirm the results of Fuglie (2007) and Cromme et al. (2010) that potato viruses are abundant in Uganda and play a major role in seed health. Furthermore, in addition to the study of Schulte-Geldermann et al. (2012) this research proved that besides PLRV and PVX, a (very) high incidence of PVM and PVS in Ugandan seed potatoes is prevalent (Figure 3.5). This high incidence of PVM and PVS was confirmed in cv. Victoria and cv. Katchpot 1; cv. Rwangume had lower incidence in PVM and a decrease after the 2nd season of PVS. These observations on PVS and PVM incidence are in line with the results of Muthomi et al. (2009) from a study in Kenya, where also lower levels of PVY were found. Currently PVA plays a less important role in seed tubers in Uganda, which is in line with the results from a study in Kenya (Were et al., 2013).

In cv. Rwangume, the highest incidence of viruses was found in the 2nd season (Figure 3.4, Figure 3.5) and the lowest yield was obtained in the 2nd season (Table 4.4). This low yield level might be caused by using less healthy seed tubers. In cv. Rwangume, a regeneration was experienced in all seed selection practices (Figure 3.4), but the highest proportion of clean tubers was found in the continuous positive-selected seed. Therefore, the study shows that regeneration of a degenerated potato crop and incomplete autoinfection are possible like Bertschinger et al. (2017) described; this depends greatly though on the potato genotype. Cultivar Rwangume as a landrace (origin unknown, Kaguongo et al., 2008) seems to be resistant against the tested viruses, which is of great importance in tropical regions (Solomon-Blackburn and Barker, 2001); the ‘regeneration’ might also explain, beside red skin and potato quality, the high acceptance of farmers (grown by 57% of all surveyed farmers, Chapter 2).

The study also confirmed findings of Gildemacher et al. (2009) that mixed virus infections are common in the informal seed system, but the data from the 1st season suggest that this might also be the case in the formal seed system. Moreover, virus incidence was often found to be more prevalent in corners or outer rows of the experiment. The situation in farmers’ fields may also be better than in small experimental plots, because it will be more easy to avoid corner parts and outer rows in a field.

The findings from Chapter 4 showed a variable, but overall positive yield effect from using positive-selected seed (Table 4.2, Table 4.3, Table 4.4, Figure 4.5). The 1st season experiments, where plant selection was done the first time in the potato plots for the next season, achieved a very high yield, with yield levels up to 39 Mg ha^{-1} in cv. Victoria (Figure 4.3). This suggests a high productivity in earlier generations as Schulte-Geldermann et al. (2012) and Demo et al. (2015) indicated. A higher incidence of major yield-reducing viruses like PLRV and PVX in later generations (Figure 3.5) might have decreased yield levels in cv. Victoria (Table 4.2, Table 4.3, Table 4.5) and confirms the results of Schulte-Geldermann et al. (2012).

In general, continued positive selection showed a higher yield per plant when compared to the continued farmers’ selected seed (Table 4.2, Table 4.3, Table 4.5), even if the difference was not always statistically significant. Inside a plot, positive-selected plants in most cases showed significantly more tubers per plant when compared to non-selected plants (Figure 4.4). The yield increase per plant (%) in continuously positive selected seed planted ranged from 0.6% to 32.7% (Table 4.2, Table 4.3, Table 4.5), with an overall of 10% yield increase across the seasons and locations compared to farmers’ selection. The low selection pressure needed in the plots might have hindered the full potential of positive selection. Another reason for not obtaining the full potential might have been the large and variable number of missing plants at harvest.

Nevertheless, positive selection works. This leads to the question: How is continuously applied positive selection working? Positive selection is based on visual inspection: the most healthy or best-looking plants in the potato crop are chosen. It will not work, when viruses show weak or mild visual symptoms, when latently virus infected plants occur and/or it will not work when the whole potato crop is 100% infected. It has to be recognised that some genotypes are more resistant to certain viruses, therefore not all daughter tubers will be infected (Chapter 3) (Bertschinger et al., 2017). Incomplete autoinfection (Bertschinger et al., 2017) depends on multiple factors, like host plant genetics, mature plant resistance, environmental factors and epigenetics. Future research is needed to develop resistant varieties.

Results from aphid catches (Figure 3.2) in the field experiments implicate the prevalence and importance of primary virus infection and confirmed seasonal peaks of vector abundance (Carli and Baltaev, 2008). Due to climate change it is expected that aphid populations will increase by 2050, hence it can lead to an increase in PVY and PLRV (van der Waals et al., 2013). Canto et al. (2009) indicated warmer temperatures can lead to faster virus replication and movement, which also can lead to an increase in virus incidences in temperature sensitive potato cultivars (Bertschinger et al., 1995). Increasing temperatures due to climate change can therefore lead to higher degeneration rates of seed potatoes. Given a higher degeneration rate due to increasing temperatures, what components are necessary to make positive selection as an on-farm seed management tool successful? Positive selection with supplementary vector management reduces the virus incidence and thereby the speed of seed degeneration. Positive selection maintains the level of quality seed tubers, therefore it becomes more attractive regarding cost effectiveness for the smallholder farmer (Thomas-Sharma et al., 2016). Potato plants are exposed and susceptible to rapid infections from neighbouring fields (Thomas-Sharma et al., 2016); therefore, the success of supplementary management choices to decrease infection rates will affect any given farmer.

In our plots bacterial wilt diseased plants were rogued (Chapter 4). As described by Thomas-Sharma et al. (2016), rogueing within one season may reduce yield, rogueing over successive cycles will reduce seed degeneration by avoiding the spread of the disease and reduce the (total) yield loss. However, own observations showed that bacterial wilt diseased plants and tubers were thrown on neighbouring fields and not destroyed, therefore rampant spread of the disease is assumed; this also confirms findings of Kigundu et al. (2019) that bacterial wilt is a major threat in Kabale district.

Insights in adoption rates and economic feasibility of positive selection

The construction of a farm typology in Chapter 2 was a valuable tool to capture farmer diversity and to associate what factors accelerate adoption. While 68% of the farms knew positive selection and the related seed plot technique, yet only 37% of the farms were using positive selection or the related seed plot technique (Chapter 2). This leads to the question: Why is the adoption rate of farmers who know the technique positive selection not higher? Chapter 2 showed that only certain types of farmers adopt positive selection. Generally, the practices of positive selection or the seed plot technique are advised for resource-poor farmers, because they lack financial capital to buy quality seed. However, these practices were also found to have a very high adoption rate in the highly innovative farms (FT 2). This might also show that FT 2 is more aware of the importance of planting good quality seed tubers. Our results are in line with those of Abdulai (2016) that adoption of agricultural innovations is positively influenced by extension services and farmer associations. Access to extension service and knowledge as well as access to land, labour and cash play a significant role in the adoption of innovative management practices (Michalscheck et al., 2018; Tadesse et al., 2017). Highly-innovative and medium-innovative farm types can invest more resources in cash and access to hired or family labourers compared to low innovative farms (Chapter 2).

It should be known that positive selection will not equally benefit every farmer; the adjusted rate of return in potato farming varied between 278 to 464% due to different yield increases and selling prices of the produce (Table 5.5). As described by Tittonell and Giller (2013) and Fermont et al. (2009) the interactions between genotype, environment and management always determine the final yield (Chapter 2, Chapter 4) and in turn affect socio-economic characteristics and priorities of the household (Chapter 2, Chapter 5) (Tittonell et al., 2010).

This study had the approach to take up and study all main agricultural management practices in a cost-benefit ratio to develop recommendations, which was suggested by Thomas-Sharma et al. (2016). Chapter 5 showed that applying positive selection as an additional management practice is extremely cost efficient: it required only a small quantity of labour days compared with other main agricultural practices in all farm types. An average investment of 4.0% on extra labour costs for applying positive selection was needed, which is a small and acceptable investment. The marginal rate of return for non-adopters in applying positive selection - with an estimated 10% yield increase by applying positive selection - was on average 1211% (Table 5.4) which is superior than the minimum of 100% (CIMMYT, 1988).

From the survey it became also obvious that harvesting selected plants separately might also not be fully understood by a hired labourer who never heard of this technology (data not shown). Farmers also mentioned regarding the question why they did not adopt positive selection that pegging plants with sticks attracts thieves and/or that sticks are removed (data not shown). Furthermore, smallholder farmers might not see a small increase as beneficial, especially if large fluctuations in yield generally occur (shown in Chapter 4). Even though positive selection requires only little investment in labour, time and cash, smallholder farmers might not be willing to invest in it, because of socio-economic conditions (Tadesse et al., 2017), or because they are merely short in labour (McCullough, 2017; Silva et al., 2019). Essential further steps regarding labour constraints in adopting a practice might be in building up and strengthening farmer cooperatives or farmer groups. Parsa et al. (2014) and Tadesse (2017) indicated that collective action is needed for adopting management practices, which can be also relevant in understanding the adoption process of positive selection. Therefore, the need of seed system intervention in social dimensions and innovations is required (Almekinders et al., 2019). However, a crucial point in advising farmers regarding management practices is improved coordination and support from the government and the private sector; this can strengthen the national and local institutional level to increase potato productivity.

6.4. Outlook on linking the integrated seed sector approach with the integrated seed health strategy

For Uganda it is estimated there is currently a seed potato demand of 239,328 Mg per year; only 0.13% of seed tubers are supplied from the formal seed sector like KAZARDI and private seed multipliers like UNSSPA (FAO, 2015; Barekye, 2019). That shows that there is little penetration from the formal seed sector system into the informal seed sector (FAO, 2016; Thomas-Sharma et al., 2016). However, potato was chosen as one of the priority crops under the Development Strategy and Investment Plan (DSIP) of the Ministry of Agriculture, Animal Industry, and Fisheries (MAAIF) which is anchored in the Comprehensive African Agriculture Development Programme (CAADP) and the National Development Plan (NDP); its increasing importance regarding food and income security has been recognised.

The Ugandan National Seed Policy has the vision of 'A competitive, profitable and sustainable seed sub-sector where farmers and all seed users have access to affordable quality seed' (Ministry of Agriculture, 2018a). The aim of the seed policy is 'to guide, promote, develop and regulate the seed sub-sector in order to ensure availability and access to safe and high-quality seed to all stakeholders for increased food and nutrition security, household income, wealth creation and export earnings' (Ministry of Agriculture, 2018a). The mission is 'to create a well-regulated seed sector that ensures availability of and access to safe and high quality seed under a pluralistic seed system'(Ministry of Agriculture, 2018a). Pluralistic is defined here as 'encompassing all stakeholders in the spirit of equity and fairness' and '(to) not preclude anyone who abides by this policy' (Ministry of Agriculture, 2018a). Uganda's goal is to harmonise the national seed policies with regional and international conventions and protocols.

In the policy, the government identifies and recognises the co-existence of the formal and the informal seed systems. The government recognises the modernisation of agriculture by increasing the quantity of quality seeds for farmers by transforming the informal seed system into a commercial seed system. To realise this goal, an intermediate seed system, namely the *integrated seed system*, helps transform the informal seed system into a fully regulated seed system. This goal for a fully regulated system is set for 2023 (Ministry of Agriculture, 2018b).

The *integrated seed system* operates with the funded Integrated Seed Sector Development (ISSD) on implementing several programmes on community-based seed production for producing quality declared seed (ISSD Uganda, 2014). The ISSD is supporting the seed potato value chain by i) decentralising the production of quality declared seed by training specialised farmer groups (Local Seed Businesses), and ii) decentralising the production of 3G tubers in potential local seed businesses. Seed tubers produced from Local Seed Businesses are inspected by the National Seed Certification services (NSCS). Local Seed Businesses are aiming to promote improved potato varieties and to develop a market-oriented seed potato sector.

Furthermore, the seed policy aims to preserve genetic diversity by conserving local varieties, but specific programmes need to be established for preserving valuable genetic resources. Programmes, which support communities in adding value to their local genetic resources, might have a strong effect on improving food security and livelihoods of marginalised communities. At the same time, those programmes contribute to the conservation of agrobiodiversity.

Seed health strategies involve areas of i) on-farm management (like positive selection) and ii) host plant resistance. Moreover, both can be combined in a periodic purchase of high-quality seed, when its economical feasible for the smallholder farmer. Calculating a seed rate of 1,500 kg ha^{-1}, with an 80-kg bag of high-quality seed for 130,000 UGX (50 US Dollar), a total of 2,437,500 UGX (937 US Dollar) is needed. This shows that only certain farm types would fall into the category of being able to purchase high-quality seed (in this case FT1 and FT 2, see Chapter 5). Selling the saved seed tubers of 1,500 kg leads to an average income of 1,037,392 UGX (398.99 US Dollar). This shows that saving seed tubers is an economically wise decision.

The two afore mentioned approaches of seed health strategies can be referred to as an *integrated strategy* for managing seed health (Thomas-Sharma et al., 2016) and offer farmers a more realistic solution (compared to the purchase of high-quality seed) for managing seed degeneration. High yield levels of high-quality seed seem to decrease after one cropping season due to a higher virus incidence (Chapter 4). The two approaches of seed health strategies are also affected by agricultural management practices of the farmer and an efficient selection procedure is needed. Our findings showed that some farms (in our case Farm Type 4, Chapter 2) did not use pesticides, which is in line with Thomas-Sharma et al. (2016) when they discussed 'out-of-reach' management practices.

Relying on certified seed from the formal seed system is a too simplistic principle in developing countries (Thomas-Sharma et al., 2016) where socioeconomic, institutional and agroecological aspects are different to those in developed countries. Difficulties for implementing the formal seed sector also lie in corruption, differences in priority, lack of enforcement, trust and infrastructure (Thomas-Sharma et al., 2016). Furthermore, many aspects like farmers seed sovereignty and biodiversity in the smallholder informal seed system play a crucial role for reorienting from the overall formal seed system (Coomes et al., 2015; Wattnem, 2016).

Positive selection being part of the informal and integrated seed sector will help improve seed quality and seed health in farmers' networks. Positive selection allows a vibrant seed system, where farmers have options and are not forced into strict seed laws.

6.5. Limitations of this study

Our study clearly indicates that positive selection is not a silver bullet that will help maximise yield levels and decrease disease levels. When positive selected seed is compared with farmers' selected seed it will yield better and will reduce certain diseases; our field experiments yielded on average 10% more, but increases in the yield per plant varied from 0.6% to 32.7% across seasons. Reasons for this variability in yield levels are diverse and will be explained below.

A large variability in yield seems a common characteristic of multi-locational trials as also described by Ronner (2018) and van Vugt (2018). A potato field in Africa is rather heterogenous in terms of disease infection and soil fertility as Gildemacher (2012) stated. This is in line with our field experiments, where sometimes a higher disease incidence was observed on 'one spot' or some parts yielded higher than other parts of the field. Variable yield levels could have been explained in assessing soil fertility. In our field experiments and on farmers' sites no soil samples were taken; it is known that a large variability can be observed within farms (Tittonell et al., 2013) which affects the crop nutrient uptake efficiency. Rainfall conditions varied across the seasons and across two sites, but no rainfall data was obtained for Experiment 3 (Hamurwa) (Chapter 3, Chapter 4).

Another limitation might be in the accuracy of self-reported estimations of yield and land areas from interviewed smallholder farmers (Chapter 2, Chapter 5); this accuracy limitation is a well-known issue in sub-Saharan Africa (Carletto et al., 2015). This is either due to lack of accurate knowledge or the unwillingness to provide correct information. On-farm measurements would have increased the accuracy of collected information but would have increased research costs tremendously and would have reduced sample size. This study did also not identify individual aphid species with the aim for better predicting virus transmission, neither did this study assessed solanaceous weed hosts which can harbour viruses. Both approaches would have needed more time and additional identification are laborious and expensive.

The survey (Chapter 2) and the field experiments (Chapter 4) showed high incidences in bacterial wilt. It was not possible to keep bacterial wilt out of our experiments (Chapter 4) and this shows the high importance of the spread and infection level as also described by Kigundu et al. (2019). Bacterial wilt varied from zero infection in the 1st location to 28% in one seed selection treatment in the 3rd location and yield losses were accordingly. As described by Gildemacher (2012), the expression of bacterial wilt is erratic and depends on soil type, humidity, temperature, crop stage, and potato cultivar. Contamination might have been possible through infected tools, spread from infected sources through run-off water, already infected soils and improper removal of wilted potatoes. It was noticed that local farmers quite often threw the infected plants and tubers after removal on neighbouring fields. Therefore, farmers should be made aware of the spread of disease and regional quarantine measures should be considered.

6.6. Concluding remarks on results

The aim of this thesis was to provide novel information regarding understanding positive seed selection by investigating it with an interdisciplinary approach. Many significant associations which contribute to more in-depth knowledge of the seed management technique of positive selection were identified.
Multi-locational field experiments under different local environmental and management conditions showed a variability in yield and virus incidences. Positive selection does fit in the current seed system for smallholder farmers and has the capacity to increase yield and reduce viruses with visible symptoms compared to farmers' selection. Nevertheless, a 100% efficiency in reducing virus incidence is not achievable and yield losses occur when 1) virus infected plants have no strong visible symptoms, 2) latently virus infected plants occur and/or 3) when almost all plants in the plot are infected. The speed of seed degeneration is not predictable, and more research of virus resistant local varieties (landraces) with farmers' knowledge can enhance the management in slowing down seed degeneration.

The construction of a farm typology was a useful method to identify farm groups in which innovation practices were taken up. These farm types were subjected to further analysis of the costs and benefits of applying positive selection. Potato production is a highly rewarding business with net benefits of an average of 5,000,000 UGX (1923 US Dollar) per ha and per season; this corresponds to 2.7 years the daily wage of what a smallholder farmer can earn (on average 5000 UGX= 1.92 US Dollar a day). It also is economically feasible to adopt positive selection in the current smallholder farm system. While positive selection is an approach which integrates in the current seed policy and strategy, institutional changes are needed to implement innovations in the smallholder farm system. Future research on factors like access to inputs, capital, land, labour, and markets are needed to consider how and why those technologies work on smallholder farms.

Previous research from Tufa (2013) showed that seed growers are hardly rewarded for their additional efforts in producing quality seed. Hence, emphasis on rewards should be given to local seed business and specialised seed growers (seed entrepreneurship); local varieties (landraces) can be produced and (inter)national seed companies will not become rampant. The seed degeneration challenge for potato producers in several developing countries is expected to be successfully managed by the approach of an integrated seed health strategy, which shifts also the focus from what is ‘agronomically’ possible towards how it is ‘socio-economical’ achievable.

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Summary

In Uganda, potato (*Solanum tuberosum* L.) is an important food and cash crop for farmers. The potato has multiple agronomic advantages above other food crops, like a short cropping cycle, high production per unit area and per unit of water, and a highly nutritious produce. In Eastern Africa potato often serves as a hunger breaking crop during food shortages. In Uganda, there is an increasing demand of ware potatoes. The districts Kabale and Kisoro, located in the Kigezi highlands (1,500- 3,000 m a.s.l.) in southwestern Uganda are the most important production areas of potato in this country. The local environmental conditions of the mountainous districts are favourable for potato cultivation, with mild temperatures, abundant rainfall and deep volcanic soils. More than 46% of the total national potato production in Uganda is produced in these two districts.

However, since 2008 the national mean potato yield has been in decline to less than 5 Mg ha^{-1} in 2016. This yield is low in comparison to the production statistics of many other countries in the region and considering that a yield of 25 Mg ha^{-1} is attainable. Low productivity of potato is associated with poor and diverse adoption of innovative crop management practices. Potatoes are vegetatively propagated by means of seed tubers. One major reason of low productivity of the crop is associated with poor quality of the planted seed tubers. Final yield and tuber quality of ware potatoes depend on the quality of the planted seed tubers. Uganda has not a well-functioning formal seed system for potato and the current seed systems are mainly organised through self-supply (informal seed system). The common way farmers select seed tubers for planting is to choose tubers from the bulk of the harvest of a ware potato stock (farmers' selection). Those seed tubers are highly degenerated. A degeneration of seed potatoes is a decline in seed potato quality by a build-up of pathogens and pests, primarily caused by viruses, over subsequent field generations. Incidence of potato viruses in potato seed tubers can be high and these viruses can significantly reduce seed tuber health status. Substantial yield reductions due to Potato leaf roll virus (PLRV) of up to 90% have been reported. Especially PLRV, Potato virus Y (PVY), and Potato virus X (PVX) cause severe yield and quality losses for potato farmers in Sub-Saharan Africa.

To overcome the existing constraint of poor seed quality in the informal seed system in Eastern Africa a seed degeneration management technology, known as *positive selection*, was found to be highly effective. In carrying out positive selection, the healthiest looking plants in ware potato crops are selected and pegged just before full flowering to identify plants of which tubers will serve as seed for the next season. Two weeks after selecting, the positive-selected plants have to be checked for being still without symptoms. At harvest, tubers from selected plants are separately collected from those of non-selected plants and used in the next season as seed tubers for the next crop. Literature indicates a higher tuber yield after one growing cycle of applying positive selection than after applying the farmers' selection method, which was associated with reduced virus incidence for PLRV, PVX and PVY.

The aim of this thesis was to provide novel information regarding understanding positive seed selection by investigating it with an interdisciplinary approach. The overall objective of this thesis was to improve the availability and production of healthy seed potatoes for smallholder farmers in southwestern Uganda by reducing degeneration caused by viruses and by stimulating the regeneration of own produced seed. The adoption and applicability of positive selection in seed production was evaluated with the current practice of farmer's seed selection.

The introduction in *Chapter 1* presents background information on Uganda and its potato production, implications of the informal seed systems and the description of positive selection. It outlines the research content with general and specific objectives including research methods used in this study.

Chapter 2 explores the uptake of innovative management practices of smallholder potato production in southwestern Uganda and the packages of practices in which farmers have adopted them. Innovative agricultural management was defined as following improved practices: (i) use of chemical fertilizer, (ii) use of organic inputs, (iii) use of fungicides, (iv) use of pesticides, (v) use of either seed plot technology and/or positive selection, (vi) use of quality declared seed (namely from the research institute KAZARDI and/or the seed growers UNSPPA), and (vii) use of sole cropping of potato. A semi-structured questionnaire was pre-tested and used to collect data in the districts Kabale and Kisoro. The multivariate statistical methods Principal

Component Analysis (PCA) and Cluster Analysis (CA) identified four potato farm types with differences in uptake of innovative farm management and accompanying differences in yields, economical return, socio-economic characteristics and access to extension services. The main findings were (i) farm types differ from high to low adoption of innovation practices and innovation packages; (ii) farm households with highest innovation adoption have a) more access to extension services and knowledge, and b) possess more land, labour and cash; and (iii) farm households with strong adoption of innovation practices generate a higher potato yield and more income. The innovation package characterised by using organic input, fungicide input, pesticide input, seed plot technique and/or positive selection, quality declared seed and sole cropping was related with the highest potato yield and more income, compared to the package using only relative frequently fungicide input and no pesticides, which was associated with the lowest potato yield and lowest income. All farm types showed similar awareness of positive selection and/or the seed plot technology, but high adoption rates were found in the highly innovative farms and semi-innovative farms. The results imply that poor farm types require improvement and support in many areas, like access to extension services and shared knowledge, bargaining power, productivity and innovation.

In *Chapter 3* the incidences of contrasting viruses across several seasons of multiplication while using different seed selection methods (positive selection, farmers' selection) and seed lots from different origin and starting quality were analysed. Three multi-season field experiments were carried out across four production seasons and at three locations in the Kabale district. The results showed that crops planted with seeds from positive selection had a reduced virus incidence compared to those from farmers' selection, thereby keeping viruses of secondary infection at lower levels in the next-season crop. However, this reduction of virus incidence by positive selection compared to farmers' selection was not found for all virus species. Positive selection demonstrated clear results for PLRV and PVX in all seed lots. Incidences of PVY and Potato virus A (PVA) were maintained mostly at levels as assessed after starting of the field experiments. The reduction was less strong for Potato virus S (PVS) and Potato virus M (PVM), likely because symptoms are poorly visible in the crop and because initial levels were often very high. One cultivar (cv. Rwangume) showed signs of incomplete autoinfection of tubers. Therefore, applying positive selection in a degenerated crop might enhance regeneration. Overall, positive selection can be a long-term strategy to keep virus incidence with clear visual symptoms in plants at lower levels than in farmers' selection. However, it is hard to flush out viruses where no obvious symptoms occur or when seed lots are fully infected.

The objective of *Chapter 4* was to understand what influence seed selection treatments have on yield and yield components in crops from different potato seed lots over several seasons from positive selected tubers compared with farmers' selected tubers. Data to study the improvement in yield were derived from the afore mentioned field experiments regarding virus incidence in Chapter 2. The fresh tuber yield per ha was divided into the following components: the plant numbers (planted, emerged, rogued, lost and harvested), tuber yield per plant, weight per tuber, number of tubers per m^2, and number of tubers per plant. Consistently for all seed lots and individual seasons in all experiments, the tuber yield per plant was always higher in the treatment of continuously positive selected plants than in the treatment with continuous selection based on the farmers' method. Positive selection gained on average a yield increase of 12%, but yield increases ranged from –5.7% to +36.9%. These yield increases were due to higher yields per plant, and mostly higher weights per tuber, whereas the numbers of tubers per plant were not significantly different. Experimentation and yield assessment were hampered by a varying number of plants that could not be harvested because plants had to be rogued from the experimental plots because of bacterial wilt (more frequent under farmers' selection than under positive selection), plants disappeared from the experimental field and sometimes plants did not emergence. Within a plot, it was shown that positive-selected plants produced significantly more seed tubers compared to non-selected plants. These comparisons indicate that positive-selected plants are more productive, making the seed selection process more efficient.

Chapter 5 assessed the time, labour and costs of positive selection invested by farmers who carry out positive selection, and to compare these costs and labour data to those of other agricultural practices. It also explored whether it is economically feasible for non-adopters of positive selection to invest in this technique by achieving a higher crop yield. This cost-benefit analysis was conducted based on data obtained from the semi-structured questionnaire which was clustered in four farm types from Chapter 2. Farms that already adopted positive selection invested on average 1.2 extra days (i.e. 2.7 extra labourer days) per acre in positive selection, with an average of 4.0% extra labour costs; this is a small share comparing it to other main variable agricultural practices. The marginal rate of return of investing in positive selection was much larger than 100% in every farm type. In the different farm types gross benefits and net benefit varied due to different yield increases and different selling prices of potatoes, indicating that some farm households benefit more than other ones. However, positive seed selection can be a valuable option for cost effective seed potato production management in the informal seed sector in Uganda.

Chapter 6 responds to each research objective and reflects on the comprehensive insights of the thesis. The interdisciplinary approach used for the study was crucial to understand positive selection. This chapter summarised the key message of the study. Positive selection does fit in the current seed system for smallholder farmers and has the capacity to keep yield at higher levels than farmers' selection and viruses with visible symptoms at lower levels. Although farms differ in the uptake of positive selection, it is economically feasible to adopt this seed management option. It can be concluded that positive selection with being part of the informal and integrated seed sector helps to improve seed quality and seed health in farmers' networks. Positive selection allows a vibrant seed system, where farmers have options and are not forced into strict seed laws.

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About the author

Uta Priegnitz grew up in Leipzig, Germany, where she first studied Sociology and Psychology at Leipzig University. She moved to Berlin to continue her studies at the Freie Universität Berlin (FU) where she completed her Diploma in Sociology and Anthropology with a focal point in Development Studies and Cultural Sociology in 2001. Her research interest shifted to agriculture, as she worked on many farms abroad (Ireland, Portugal/Madeira). She decided to advance her knowledge by continuing her studies at the Humboldt University Berlin (HU) in Integrated Natural Resource Management, where she also worked as a student counsellor at the same faculty. She specialised her master's degree in Plant Production and Organic Farming. In collaboration with the federal research centre Julius Kühn Institute in Germany she carried out her MSc thesis 'The control of the Colorado potato beetle in organic farming' in 2009. After this, she worked in Teagasc, Johnstown Castle/ Environment Research Centre in Ireland on the topic of 'Greenhouse gas emissions on Irish grassland' until 2010. Her longing to work and travel to Iceland was realised when working on a remote dairy farm in Iceland. During this stay she applied for her PhD position from the Erasmus Mundus Joint Doctorate Programme - Agricultural Transformation by Innovation (AgTraIn) scholarship, and it was granted in 2012. Her PhD project - which resulted in this thesis - focused on understanding seed potato selection practices in Uganda from an interdisciplinary point of view.

List of publications

Journal papers

Priegnitz, U., Lommen, W. J. M., van der Vlugt, R. A. A, Struik, P. C. (accepted) Potato yield and yield components as affected by positive selection during several generations of seed multiplication in southwestern Uganda. Potato Research

Priegnitz, U., Lommen, W. J. M., Onakuse, S., Struik, P. C. (2019) A farm typology for adoption of innovations in potato production in southwestern Uganda. Frontiers in Sustainable Food Systems, 3(68). http://doi.org/10.3389/fsufs.2019.00068

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Priegnitz, U., Lommen, W. J. M., van der Vlugt, R. A. A., Onakuse, S., Struik, P. C., 2016, Virus control in Ugandan seed potato tubers over multiple field generations by applying different seed technologies, '16th triennial meeting of the Virology Section **of the European Association of Potato Research (EAPR)** with the 8th annual meeting of PVYwide', Ljubljana, Slovenia

Priegnitz, U., Lommen W., van der Vlugt, R., Onakuse, S., Struik, P., 2014, Improving Seed Potato Quality in Southwestern Uganda for Strengthening Food and Cash Security, Tropentag, 'Bridging the gap between increasing knowledge and decreasing resources', Prague, Czech Republic

Priegnitz, U., Kühne, S.; Ellmer, F.; Moll, E.; Kowalska, J., 2008, Effect of Spinosad, Neem and *B.t.t.* on the control of the Colorado potato beetle (*Leptinotarsa decemlineata* Say) in organic farming, 1. Nachwuchswissenschaftler- Forum, Quedlinburg, Germany

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Adoption of different seed potato management practices regarding virus incidence; virus diseases of potatoes and production of seed-potatoes

Writing of project proposal (4.5 ECTS)

- Improving seed potato quality in south-western Uganda by designing alternative technologies and supply systems (2012, 2013)

Post-graduate courses (12.6 ECTS)

- Introductory course to doctorate research within agricultural development, food chains and innovation; AgTraIn (2012)
- Sampling in space and time for survey and monitoring of natural resources; WUR (2013)
- Joint field course; AgTraIn (2014)

Deficiency, refresh, brush-up courses (4.5 ECTS)

- Fundamental and applied virology; WUR (2013)
- Basic statistics; WUR (2016)

Competence strengthening / skills courses (6.6 ECTS)

- PhD Competence assessment; WUR (2012)
- Presentation skills; WUR (2013)
- Scientific writing; WUR (2013)

- Project and time management; WUR (2013)
- Career assessment; WUR (2016)

PE&RC annual meetings, seminars and the PE&RC Weekend (2.1 ECTS)

- PE&RC First years PhD weekend (2012)
- PE&RC Day (2012)
- PE&RC Last year PhD weekend (2016)

Discussion groups / local seminars / other scientific meetings (5.2 ECTS)

- Contested agronomy: the politics of agricultural research (2013)
- AgTraIn: scientific dissemination and communication (2014)
- Discussion group sustainable intensification of agricultural systems (2015)
- Biocomes seminar (2017)

International symposia, workshops and conferences (5.2 ECTS)

- Tropentag; poster presentation; Prague, Czech Republic
- Research and knowledge transfer for global food security seminar; poster presentation; Dublin, Ireland
- EAPR Virology section meeting; oral presentation; Ljubljana, Slovenia

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