Identifying and using tuber characteristics to predict potato keeping quality

by

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Declaration

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Summary

Potato production in South Africa occurs in all nine provinces of South Africa and it is further divided into 16 production areas. The trial was undertaken in the Sandveld and Ceres production areas, which are characterised by dry and warm weather in summer, which presents obvious challenges to produce high-volume quality potatoes.

A macronutrient that is very important for cell wall strength of potato tubers is calcium (Ca). In a previous study, no correlation between keeping quality and tuber Ca content was found (Bester, 1993). The reaction of Ca with organic acids might be part of the reason no correlation between keeping quality and tuber Ca could be found (Venter, 1989). Calcium oxalate forms when Ca reacts with organic acids and the cells it forms in are referred to as idioblasts. Calcium and magnesium (Mg) are strongly competitive and it seems that the plasma membrane binding site at the root has higher affinity for Ca^{2+} than for the highly hydrated Mg^{2+} (Marschner, 1995). Calcium has the ability to form a insoluble complex with pectin due to the free carboxyl groups on the pectin chain (Walter, 2012). Pectin methylesterase (PME) is an enzyme responsible for removing the methoxyl groups and enabling divalent cations Ca^{2+} and Mg^{2+} to react with pectin, creating rigid structures with an increase in firmness (Tajner-Czopek, 2003). Due to the high immobility of Ca in plants it is sometimes hard to increase the Ca content in tubers.

On the other hand, Mg is mobile in the plant and increasing tuber concentrations is not as difficult as Ca, although Mg deficiencies caused by cation competition is a global phenomenon (Marschner, 2012). A study done in South Africa on several cultivars showed that of all the cultivars tested, Sifra had the lowest Mg content and that Fianna had the highest (Van Niekerk, 2015). Potato is highly susceptible to Mg deficiency, which has been shown to particularly affect the carbon assimilation and the transformation of energy (Hochmuth, 2007; Barker and Pilbeam, 2015). Considerable fewer studies have been done on Mg to the extent that it is often dubbed the “orphan nutrient” compared to Ca (Rosanoff, 2010).

When producers export or sell their seed- or ware potatoes it is important for the buyer to know in advance the quality of the product. If the keeping quality can be predicted it will help both the producer and buyer to know the quality of the product and compensation can then be arranged more accurately, since good keeping quality

potatoes should have higher value than poor keeping quality potatoes. To predict the keeping quality of seed- and ware potatoes, various quality characteristics must be identified and used. The main objective for this study was to develop a measuring tool that can be used to routinely predict the keeping quality of a tuber.

Tubers were sampled throughout 2016 season and partially through the 2017 season. Inspection for IBS and hollow heart were assessed to see if any of the quality characteristics could correlate with these disorders. Tubers were stored at 25℃ and 5℃ respectively, while mass loss was determined as percentage (%) loss throughout the storage period. Different quality characteristics were measured to use in a prediction model.

Opsomming

Aartappelproduksie in Suid-Afrika vind plaas in al nege provinsies van Suid-Afrika en dit is verder opgedeel in 16 produksie areas. Die proef is in die Sandveld en Ceres produksie-areas uitgevoer, wat gekarakteriseer word deur warm weer in die somer wat uitdagings vir die produksie van hoë volume kwaliteit aartappels daarstel.

Die makronutriënt kalsium (Ca) is baie belangrik vir selwandsterkte in aartappelknolle. In ‘n vorige studie is daar geen korrelasie gevind tussen houvermoë en knol Ca inhoud nie (Bester, 1993). Die reaksie tussen Ca en organiese sure mag deel wees waarom geen korrelasie tussen houvermoë en Ca gevind kon word nie (Venter, 1989). Kalsiumoksalaat vorm wanneer Ca reageer met organiese sure en die selle wat vorm, word idioblaste genoem. Kalsium en magnesium (Mg) is sterk kompeterend en dit lyk asof die plasmamembraanbindingsplekke by die wortel hoër affiniteit vir Ca^{2+} het as vir die hoogs gehidreerde Mg^{2+}(Marschner, 1995). Kalsium het die vermoë om ŉ onoplosbare kompleks met pektien te vorm weens die vrye karboksielgroepe op die pektienketting (Walter, 2012). Pektienmetielesterase (PME) is ŉ ensiem verantwoordelik vir die verwydering van die metoksielgroepe groepe en dit laat toe dat divalente katione Ca^{2+} en Mg^{2+} reageer met pektien om sterk verbindings te vorm met hoër fermheid tot gevolg (Tajner-Czopek, 2003). As gevolg van die hoë immobiliteit van Ca in plante, is dit soms moeilik om die Ca-inhoud in die knolle te verhoog.

Hierteenoor is Mg, ŉ mobiele element in die plant en om die konsentrasie Mg in die knol te verhoog is makliker as om Ca te verhoog, alhoewel Mg-tekorte as gevolg van katioonkompetisie ŉ globale verskynsel is (Marschner, 2012). Verskeie kultivars is in ŉ Suid-Afrikaanse studie gerbruik en van die getoets, het Sifra die laagste knol-Mg-inhoud en Fiana die hoogste gehad (Van Niekerk, 2015). Aartappels is hoogs vatbaar vir Mg tekorte, dit is al spesifiek getoon dat dit koolstofassimilasie en transfermasie van energie negatief affekteer (Hochmuth, 2007; Barker and Pilbeam, 2015). Aansienlik minder studies is al gedoen op Mg tot so ‘n mate dat dit gereeld beskryf word as die weeskind van nutriënte tenopsigte van Ca (Rosanoff, 2010).

Wanneer produsente hul saad- of tafelaartappels uitvoer, is dit belangrik vir die koper om vooraf te weet wat die kwaliteit van die produk is. Indien die houvermoë voorspel kan word, sal dit beide die verkoper en koper bevoordeel want dan kan vergoeding vir die produk meer akkuraat wees, aangesien aartappels met goeie houvermoë beter pryse behoort te kry as die met swakker houvermoë. Om houvermoë te voorspel van saad- en tafelaartappels, moet verskeie kwaliteitseienskappe geïdentifiseer en gebruik word. Die hoofdoelwit van hierdie studie is om 'n metingsinstrument te ontwikkel wat gebruik kan word om die kwaliteit van 'n knol herhaaldelik te voorspel.

Knolmonsters is reg deur die 2016-seisoen en deels deur die 2017-seisoen geneem. Inspeksie vir interne bruinvlek en holhart is gedoen om te kyk of enige van die kwaliteitseienskappe kon korreleer met die afwykings. Knolle is geberg by 25℃ en 5℃ en massaverlies was bepaal as persentasie (%) verlies deur die hele bergingsperiode. Verskeie kwaliteitseienskappe was gemeet om in die voorspellingsmodel te gebruik.

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Preface

This thesis is presented as a compilation of 5 chapters. Each chapter is introduced separately and is written according to the style of the journal South African Journal of Plant and Soil to which Chapters 3 and 4 will be submitted for publication.

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CHAPTER 1

1.1 BACKGROUND

Cultivated potatoes (*Solanum tuberosom* L.) that are commercially produced today were selected from the *S. brevicaule* that originated from the Andes and Chile regions in South America (Spooner and McLean, 2005). In terms of mass production potato is the fourth largest crop after wheat (*Triticum aestivum*), rice (*Oryza sativa*) and corn (*Zea mays)*. Its use as a cattle feed has decreased and it is mainly consumed for human nutrition as a fresh- and/or as an industrially processed product (Fabeiro et al., 2001). Potatoes are classified as annual, cool seasoned plants. However, it can survive from one season to the next through tubers in the ground. Even though it is a cool seasoned crop sufficient yield was previously demonstrated for warmer regions too (Navarre and Pavek, 2014). Potato's equatorial origin caused it to be short day adapted for tuberization but most modern cultivars do not have a strict need for short-days in order to form tubers (Navarre and Pavek, 2014). Tubers are low transpiring; botanically stem tissue that forms on the end of a stolon. The definition of a stolon is a lateral shoot that forms from the basal stem nodes, these stem nodes show minor leaf expansion and grows in the same direction as gravitational pull (Booth, 1963).

Since 1979 the land available in the world for potato production has decreased by over 1 million hectares (ha) (Fabeiro et al., 2001). The soils under potato cultivation in the Sandveld and Ceres areas cannot obtain substantial yields without high amounts of fertilisers. In the Sandveld average yields reach about 49.2 tons ha^{-1} (Van der Waals et al., 2016), but much higher yields are possible (Franke et al., 2011). Around 38 kg of potatoes are consumed annually per capita in South Africa (Department of Agriculture, Forestry and Fisheries, 2016) and producing high volumes of potatoes in warm and dry conditions can sometimes compromise its quality. Global warming is causing increased carbon dioxide (CO_2) levels and extremes in climatic conditions. Excessive heat during tuber bulking can decrease tuber quality and inhibit crop growth (UNECE, 2014). These aforementioned factors as well as an ever-increasing and expanding global population are creating challenges for agronomist to increase food production, including potato production.

In South Africa potatoes are produced under different climatic conditions, but they are susceptible to various physiological and nutritional disorders that can affect its quality. Specific gravity (SG) is used as a standard in the USA , Holland and RSA for potato quality (Lugt, 1961; Niederwieser and Raan, 2017), although higher SG does not necessary correlate with better keeping quality (Venter, 1989). Nutrients present in dicotyledon cell walls include Ca, potassium (K), sodium (Na), Iron (Fe), magnesium (Mg), silicon (Si), zinc (Zn) and boron (B). Conjointly they can account for up 5% of the dry mass (Epstein, 1999; Welch and Shuman, 1995).

The two most prominent physiological disorders that negatively affect the quality of potato tubers are hollow heart and internal brown spot (IBS). Both of these are at least partly caused by nutritional stress. Through lime applications and thus increased calcium (Ca) in the soil, Combrink and co-workers managed to lower the incidence of IBS and improve the quality of tubers (Combrink et al., 1974; Kleinhenz et al., 1999). In contrast, other researchers struggled to find any correlation between keeping quality and tuber Ca content (Bester, 1993). In a more recent study an inverse correlation between IBS and Ca concentration of the medulla was demonstrated (Kempen, 2012). Attempts to increase tuber Ca through foliar applied Ca failed and it was suggested that loss of Ca because of its reaction with organic acids might be one of the reasons no correlation between keeping quality and tuber Ca content could be found (Venter, 1989). Alternatively, Ca uptake in the tuber only occurs close to the tuber, while foliar applied Ca will most likely only increase Ca in the leaves and not the tubers and thus have limited impact to rectify Ca deficiencies in tubers (Busse and Palta, 2006).

Studies showed that the Mg concentration in tomato shoots and fruits decreased with an increase in Ca fertilisation (Gunes et al., 1998; Paiva et al., 1998). Even when dolomitic lime is fertilised Mg deficiencies might still appear (Barker and Pilbeam, 2015). The reason for this might be due to differences in solubility of magnesium carbonate

($MgCO_3$) and calcium carbonate ($CaCO_3$). After approximately 4 months all the Mg had dissipated with only Ca available for plant uptake (Barker and Pilbeam, 2015). A study showed that after a 6 month storage period the 60 kg ha^{-1} magnesium oxide (MgO) fertilisation resulted in the lowest fresh mass losses for two mid-early cultivars and could be associated with increased keeping quality (Wszelaczynska and Poberezny, 2011).

The main objective for this study is to develop a measuring tool that can be used to routinely predict the physiological quality of a tuber. This quality norm must be able to correlate both with the quality of seed- and ware potatoes. The secondary objectives include taking measurements of different factors such as fertilisation, soil- and irrigation water composition. An attempt to incorporate physiological disorders such as IBS and hollow heart into this model was also made. These factors might help to explain differences in physiological quality of potatoes. The correlation of mass loss during storage with periderm damage (since skinning is correlated with phellogen activity) was also assessed. The possibility to incorporate this parameter into the keeping quality model will be determined.

The possibility of predicting mass loss during storage has been studied, one such study was done using mass potato storage under cooling conditions and the amount of diffusion through the skin was used to predict mass loss rate in kg m^{-2} (Xu and Burfoot, 1999). In another study focused on improving the quality of ware potatoes in terms of fewer sprouting potatoes. It was done with computer modelling and the focus was on the storage facility and not the tubers itself (Xu et al., 2002). A study done on predicting mass loss during storage for processed potatoes concluded that skin set (physical maturity) should be included in future mass loss models and that cultivar-specific models should be considered. Those also stated the importance of prediction models to growers and the processing industry (Heltoft et al., 2017).

1.2 SUMMARY

It remains difficult to predict good quality seed- and ware potatoes and when creating a quality prediction model numerous factors should be considered. Quality must be defined and the factors that influence it must be identified. Some of the quality characteristics include nutritional status, skin strength and specific gravity (SG). Previous studies were done on predicting mass loss during storage but none of these studies focused on potato nutrition in terms of specific nutrients and the possible effect it can have on mass loss and the quality of the potatoes. Differences in quality due to size and seasonal variation must also be considered. Increases in good quality (staple) food production will have to happen on a decreasing amount of arable land. With these challenges in mind, producing quality potatoes is an ever-increasing problem and quality must not be compromised when high food production is required since it directly impacts human health.

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CHAPTER 2

Literature Review

2.1 CROP REQUIREMENT

Potatoes have a base temperature of 5°C below which growth is negligible (Sahu, 2003). Optimum daily temperatures for potatoes are 18-20°C and a night temperature of below 15°C is needed for tuber initiation. Usually tuber initiation commences 20 to 30 days after emergence and last up to two weeks (Mihovilovich et al., 2014). Optimum soil temperature for tuber growth has been established between 15-18°C, whereas soil temperatures below 10°C and above 30°C have a negative impact on tuber growth. For a crop growing 120 to 150 days, the crop water requirement varies between 500 to 700 mm a season. High productive soils are well drained, aerated and porous (Brown and McLean, 1984; Cao and Tibbitts, 1994; Doorenbos and Kassam, 1979). All plant nutrients are available at the pH range 5.5-6.5 (Lucas and Davis, 1961) and potatoes are classified as very tolerant of acidic conditions even up to a pH of 5.0 (Hochmuth, 2007). Potatoes grown under irrigation are mostly grown on ridges with a sowing depth of 5-10 cm and plant spacing of 0.75 m between rows and 0.3 m between plants (Doorenbos and Kassam, 1979; Hochmuth, 2007) depending on seed size and sprouting. In temperate regions like the Western Cape ridges are earthed up to avoid greening.

In terms of the South Africa Seed Potato Certification Scheme about 10 000 ha of certified seed potatoes are produced annually (Denner et al., 2012). Potatoes of 100 g or smaller are marketed for seed if certified, above this mass tubers are sold as ware potatoes in seed production systems. Elite, Class 1 and Standard are the classification used for seed. The quality (in descending order) of ware potatoes is classified into Class

1, 2 and 3. The size classification entails baby (5-50 g), small (50-100 g), medium (90-170 g), large-medium (150-250 g) and large (>250 g) (Denner et al., 2012). Plant density for seed growers in South Africa can vary between 25 000 tubers ha^{-1} to 70 000 tubers ha^{-1} (Uys, 2015). It is recommended to store potato seed at 90% relative humidity (RH) at 2-4°C for extended storage and at 7-10 °C for short storage. Seeds must be cured before planting and this is done by placing it at 16-18 °C with 90-95% RH for ten to fourteen days. Next it is moved to 18°C for another ten to fourteen days before being transplanted (Hochmuth, 2007).

2.2 CULTIVAR SELECTED

Cultivars in South Africa are grouped into short (70-90 days), short-medium (80-100 days), medium (90-110 days) and medium-long (100-120 days) (Denner et al., 2012). Sifra is the second highest seller on the South African fresh market after Mondial ("Top ten cultivars on markets: 2016 calender year, 2017). The cultivar Sifra is classified by Ćota et al. (2010) as a short-medium to medium-long variety containing large round oval tubers, yellow epidermis, with light yellow flesh. It accumulates high DM content and strong to fairly solid meat consistency (Ćota et al., 2010). Sifra was bred by C.J. Biemond at HZPC research in Meltslawier in the Netherlands in 1995. After crossing Mondial and Robinta the variety was selected from the F1 progeny based on yield, internal- and external quality and resistance to different pest and disease (Canadian Food Inspection Agency, n.d.). Character of the seed parent include long oval tuber shape and light cream tuber flesh colour while the pollen parent has a red tuber skin colour, light yellow tuber flesh colour and very shallow eyes. Selection was done for more than 10 years and trials for agronomic characteristics, disease resistance and quality were done for more than 15 years in various countries (Plant Varieties Journal, 2012). The Sifra cultivar has an upright growth habit, medium thick main stem with low swelling at nodes and the foliage structure is intermediate type (Canadian Food Inspection Agency, n.d.).

Sifra has a strong foliage development and percentage (%) DM of 19.7%, starch content of 13.9% and specific gravity (SG) of 1.077. Other characteristics include moderately short dormancy, sensitive to internal bruising and large tubers with 9-11 tubers per plant (HZPC, 2016). True dormancy has also been referred to as innate dormancy and the period following innate dormancy when bud growth is inhibited has been termed as enforced dormancy (Jeffries and Lawson, 1991). The dormancy period can refer to the number of days to bud growth from harvest, haulm removal or tuber initiation (Struik and Wiersema, 1999). When a tuber starts to sprout the apical eye will be the first to start growing (Artschwager, 1924; Kumar and Knowles, 1993). Temperature above 15℃ causes apical dominance to promptly appear at the terminal bud while at 10℃ numerous buds begin to grow. When tubers was stored at 1-5℃ for a few months and moved thereafter to higher temperature all the buds started to grow, but growth are later inhibited (Goodwin, 1963).

An increase in DM above 20% will increase the susceptibility to bruising. For yields of 50 t ha^{-1} it is recommended to fertilise between 120-150 kg ha^{-1} nitrogen (N) and 360 kg ha^{-1} K depending on the soil type. A study done in South Africa on several cultivars showed that of all the cultivars tested Sifra had the lowest Mg content and that Fianna had the highest (Van Niekerk, 2015). Another study showed similar results for Fianna, but Sifra had an above average Mg concentration of the cultivars tested (Ngobese et al., 2017).

Sifra has an early skin set and can be stored for medium-long periods in a well ventilated cold room and storage at 3 C is recommended (HZPC, 2016). The cultivar Sifra is an excellent yielding potato (Wes Vrystaat Aartappel Moerkwekers, n.d.) and has a seven out of ten rating for resistance against scab (HZPC, 2016). Potatoes South Africa has classified fresh potatoes into three categories namely waxy, waxy/floury and floury. Waxy potatoes are low in starch and have high moisture content. Waxy/floury potatoes such as Sifra have a floury feel and have medium moisture content. Floury potatoes have a high starch content and a low moisture content (Potatoes South Africa, n.d.). Larger cells and starch granules are associated with floury potatoes while smaller cells and starch granules are associated with waxy cultivars. “Wes Vrystaat Moerkwekersvereniging” have the breeders’ rights and are the distributors of the Sifra cultivar in South Africa (Potatoes South Africa, n.d.).

2.3 CALCIUM UPTAKE, DISTRIBUTION AND ROLE

The uptake of Ca is confined to the young root tips where it is transported across the apoplast (Robards et al., 1973). The main mechanism for Ca transport in plants is transpiration (Busse and Palta, 2006). This means that the high transpiring leaves will receive exceedingly more Ca than the low transpiring tubers. It has been hypothesised that high transpiring organs receive Ca during the day via the transpiration stream and that slow growing tissue receives Ca during the night due to root pressure (Clarkson, 1984). Potato tubers rely on the tuber roots, stolon roots and tuber-stolon junction roots for transport of water and Ca to them (Busse and Palta, 2006). Previous studies conducted with radioactive ^{45}Ca demonstrated that only an insignificant amount of Ca was transported from the soil across the periderm, even after 8 days (Busse and Palta, 2006). These results also showed that hardly any Ca is redistributed from the phloem to the tubers or the main roots and no Ca is transported from the main roots to the tubers.

It seems that Ca^{2+} enters the xylem from both the symplastic and the apoplastic pathway, but no transporter for xylem loading has yet been found, thus apoplastic transport for Ca distribution to shoots are the accepted transport mechanism (White and Broadley, 2003). Calcium uptake from the soil occurs through mass flow and root interception (Barber, 1966) , movement of ions through walls of root cell is a passive, non-metabolic process driven by mass flow or diffusion. In barley, uptake seems to be restricted to the apical region (Taiz and Zeiger, 2010). Root architecture may play a role in Ca^{2+} uptake since its uptake correlates better with number of root tips than root length (Rengel, 1999). Calcium is considered immobile constricting translocation in the phloem thus transportation can only occur via the xylem and only one direction transport can occur (White and Broadley, 2003).

It is possible that Ca is transported as a cation or cation complexes with organic acids in the xylem (White and Broadley, 2003). Calcium enters the cell by diffusion down the electrochemical-potential gradient, but is actively exported from the cytosol at both the plasma membrane and the tonoplast. Assimilation of Ca occurs by the formation of electrostatic bonds and coordination of complexes with phospholipids, amino acids and other negatively charged molecules. An example of an electrostatic complex includes the formation of Ca pectate from the divalent Ca cation and pectate (Taiz and Zeiger, 2010). Calcium distributions in plants are categorised into forms that are either physiological active or inactive. Active forms include free ions; Ca bound to organic acids, chlorides, nitrates, proteins and pectins whereas inactive forms include insoluble oxalate, silicate, phosphate and carbonate Ca (Himelrick, 1981). Starch occurs in the cortical cells of the stolon and numerous small Ca oxalate crystals are found in other cells of the stolon (Harris, 1992). Calcium oxalate mostly forms intracellularly in cells referred to as idioblasts. Crystal formation are tightly coordinated with cell growth and expansion (Franceschi and Nakata, 2005) and increasing the Ca levels sometimes elevates the number of crystals in plants (Kostman and Franceschi, 2000). Hypotheses explaining the reason for the existence of Ca oxalate includes Ca regulation, detoxification of heavy metals or oxalic acid, ion balance, plant firmness and gathering and reflection of light (Schürhoff, 1908; Franceschi and Horner, 1980; Franceschi, 2001).

Calcium is an essential macro-nutrient in plants and functions in the cell walls as a structural component in cell division, cell elongation and regulates membrane permeability. It also acts in the plant as a secondary messenger responding to environmental and hormonal signals (White and Broadley, 2003). Calcium also increases the activity of certain enzymes (Agrios, 2005; He et al., 2015). Evidence suggest that Ca can improve membrane stability and affect potatoes resistance to heat stress (Palta, 1996). As previously mentioned, another function of Ca is to form salts with pectins, but boron (B) can affect the utilisation of Ca in cell wall formation. Calcium increases disease resistance against some pathogens and it is believed that the effect that Ca has on the cell wall composition helps with resistance to pathogen penetration (Agrios, 2005). Calcium also plays a role in defence against post-harvest pathogens; a reduction of decay is seen with increased Ca concentrations, which is likely due to the increased cell wall structure (Conway et al., 1994). Potato tubers grow mainly through cell elongation (Reeve, 1969), longitudinal cell division is halted after tuber reaches 0.8 cm diameter, while cell enlargement in both the pith and cortex continues until the end of tuber growth (Xu et al., 1998). The role that Ca plays in cell elongation is seemingly very important (Venter, 1989).

Symptoms of Ca deficiencies consist out of necrosis of young meristematic areas where cell division and wall formation are the fastest, such as in young root and leaf tips. Shoot tip necrosis is an example of a Ca deficiency and is characterised by the browning of the shoot tip, loss of apical dominance and the formation of lateral branches on the shoot (Mccown and Sellmer, 1987; Taiz and Zeiger, 2010). Disorders caused by Ca deficiencies include IBS of potatoes, "bitterpit" in apples (*Malus domestica* Borkh.), black heart in celery (*Apium graveolens*) and blossom end rot in tomatoes (*Solanum lycopersicum*) (Barker and Pilbeam, 2015). Black spot bruising in potatoes caused by injury or impact during harvesting, handling or storage can be significantly decreased when the tuber Ca levels are ≥250 ppm (Karlsson et al., 2006). Goldspot is a disorder occurring in tomato fruits and it is caused by an excess of Ca oxalate, especially when occurring later in the season and it is aggravated with high temperature (Den Outer and Van Veenendaal, 1988). Peteca, a disorder containing brown spots on the rind of lemons (*Citrus limon* Burm f.), is also associated with excess Ca oxalate as well as low B concentrations (Storey and Treeby, 2002).

The factors that effect the availability of Ca^{2+} to plants are total Ca supply, counter-ions, pH and the ratio of other cations to Ca^{2+} (Grattan and Grieve, 1998). Calcium and Mg are strongly competitive and it seems that the plasma membrane binding site at the root has higher affinity for Ca^{2+} than for the highly hydrated Mg^{2+} (Marschner, 1995). When the salt concentration in the root area increases the demand for Ca by the plant also increases (Bernstein, 1975; Kreij, 1999). A decrease in uptake of Ca may occur due to precipitation, ion interactions and increase in ion strength which decrease Ca availability in the soil (Suarez and Grieve, 1988). The severity of disorders caused by Ca in saline soil depends on types of ions that affect the salinity and environment (Grattan and Grieve, 1998). Salinity dominated by sodium (Na^+) reduced Ca^{2+} availability, transport and mobility to the actively growing regions of the plant causing an overall decrease in plant quality (Grattan and Grieve, 1998). Potatoes are classified as moderately sensitive to saline conditions (Bernstein et al., 1951; Doorenbos and Kassam, 1979) and Ca ions play a key role in minimizing the uptake of Na^+ from the soil solution through increasing potassium (K) transporter selectivity at the expense of Na^{+} uptake (Taiz and Zeiger, 2010). A study was conducted testing the effect of B on Ca uptake and a decrease in Ca uptake in micro propagated plantlets was found in some cultivars with an increase in B levels. Thus excessive B may contribute to calcium deficiency related disorders (Abdulnour et al., 2000).

Nutrient concentrations are predominantly higher in the skin than the flesh except for phosphorus (P), sulphur (S) and chlorine (Cl). Dietary significant nutrients iron (Fe), zinc (Zn) and Ca concentrations are much higher in the skin than the flesh. On a dry mass basis most nutrient concentration gradient, except K, decrease from the stem end to the bud end. Calcium concentration also decreases from the periphery to the centre (Subramanian et al., 2011). It is very important to note that there is a bias when overall Ca is compared in large tubers since the periderm contains much more Ca than the flesh (Bamberg et al., 1993).

2. 4 CALCIUM PECTATE

Tubers are comprised of parenchyma cells containing mostly starch granules as well as narrow, non-lignified, primary cell walls (Parker et al., 2001). Cell walls and middle lamella of tuber cells approximately contain 60% pectin, 28% celluloses and 10% hemicelluloses (Van Dijk et al., 2002). Pectin is a very complex molecule and it is important in the cell wall of many plant structures and subsequently has an important role in ripening, storage and in processed plant materials (Schols et al., 2009). Pectin is biochemically defined as a group of polysaccharides abundant in galacturonic acid.

Pectic polysaccharides believed to be present in the cell walls of dicotyledons include homogalacturonan (HGA), rhamnogalacturonan 1 (RG1) and rhamnogalacturonan 2 (RG2) and they create a pectin network in the primary cell wall as well as the middle lamellae (Willats et al., 2001). Approximate portions of pectin polysaccharides in tubers are HGA 20%, RG1 75% but RG2 is undetermined (Mohnen et al., 2008). Pectic acid is HGA with low or no methyl esterification (Rose, 2003) and pectates are normal or acid salts of pectic acid (Rodrigues and Fernandes, 2012). Calcium has the ability to form an insoluble complex with pectin due to the free carboxyl groups on the pectin chain (Walter, 2012). Moreover, it can form with both neutral and acid carbohydrates (Angyal, 1989). When cells mature a decrease in intensity of methyl esterification of HGA can occur and it is believed that the cross-linking between the divalent cation Ca^{2+} and HGA increases with concomitant strength build-up of the cell wall (Willats et al., 2003). Pectin methylesterase (PME) is an enzyme responsible for removing the methoxyl groups and enabling divalent cations Ca^{2+} and Mg^{2+} to react with pectin and thus forming rigid structures with an increase in firmness (Tajner-Czopek, 2003). A study done on transgenic potatoes overexpressing PME showed to be more sensitive to high and low aluminium (Al) levels due to inhibition of root elongation compared to unmodified plants (Schmohl et al., 2000). The other two pectins present in the cell wall, RG1 and RG2, also contribute to cell adhesion, but their roles are more complex and less studied (Daher and Braybrook, 2015). Studies show that the B requirement of plants is correlated with the cell wall pectin content in plants (Rose, 2003) and that cross-links between RG2 and borate-diester also contributes to cell wall strength (O'Neill et al., 2004).

The idea that the texture of cooked potatoes are influenced by cell contents especially pectin has been suggested from an early date (Talburt and Smith, 1987). The correlation coefficient of textural quality of cooked potatoes with starch content was found to be 0.84, but the multiple correlation coefficient with starch, pectin Ca and total pectinate was 0.96 (Bettelheim and Sterling, 1955). It has been found that hard water, water with >500ppm Ca or Mg (Denner et al., 2012), increases the firmness of tissue (Bigelow and Stevenson, 1923). Increased compaction of potatoes occur when cooked with the addition of Ca cations (Keijbets et al., 1976). Calcium pectate is the wall component that was identified for being responsible for the firming effect in canned tomatoes (Loconti and Kertesz, 1941). Softening by cooking is often associated with changes in the properties of pectin substances (Walter, 2012). Pectin substances are more readily solubilised than other cell wall polymers although the ability to extract pectin varies widely from species to species (Walter, 2012). Unlike the cell walls of the parenchyma, limited knowledge on the polysaccharides that occur in the cell walls of the periderm exist (Harris et al., 1991).

2. 5 MAGNESIUM UPTAKE, DISTRIBUTION AND ROLE

Magnesium was first considered to be a plant essential nutrient in 1875, thirteen years after the element Ca (Reed, 1942). Uptake of Mg from the soil occurs through mass flow and root interception. In addition, plant Mg uptake is only possible in its cation form Mg^{2+}. The bulk of Mg uptake in potato tubers occurs during tuber initiation (Zhao et al., 2010). Magnesium also enters the cell by diffusion down the electrochemical-potential gradient and it is actively exported out of the cell.

Magnesium is classified as a macronutrient in plants (Epstein, 1972) and unlike Ca it can be transported through both the xylem and phloem meaning that it is mobile in the plant and redistribution can occur (Taiz and Zeiger, 2010). It functions in the plant as a cofactor for numerous enzymatic processes associated with photosynthesis and respiration. Magnesium is also an integral constituent of the chlorophyll molecule (Taiz and Zeiger, 2010). Inadequate Mg will also affect the carbon assimilation and the transformation of energy (Barker and Pilbeam, 2015). In Mg deficient potato tubers a decrease in starch can be observed due to decreased export of carbohydrates from source to sink (Werner, 1959).

Potato is a highly susceptible vegetable to Mg deficiency (Bear et al., 1951; Hochmuth, 2007). One of the first Mg deficiency discoveries were on tobacco (*Nicotiana tabacum*) and it was called “sand drown” because it occurred in highly leached sandy soils (Garner et al., 1923). Leaching of Mg occurs in sandy soils and deficiencies will most likely occur in highly acidic sandy soil (Barker and Pilbeam, 2015). A study done with nutrient film showed that potatoes with low (5 µM) or high (4.0 mM) Mg increased dark respiration and lowered the photosynthesis rate compared to Mg concentrations ranging from 0.25–1 mM (Cao and Tibbitts, 1992). A study showed that suboptimum Mg concentrations in tomato did not affect the growth, but the acquisition of assimilates in the shoot might have been the cause of decreased transportation (Carvajal et al., 1999).

Deficiency symptoms in the plant can occur because of irregular water availability, poor drainage, leaching, low pH, low temperature or competition with other cations. Other cations compete with Mg^{2+} uptake in the order of K^{+}> NH_4^{+}(ammonium)>Ca^{2+}>Na^{+} (Barker and Pilbeam, 2015). Magnesium deficiencies caused by cation competition is a global phenomenon (Marschner, 2012). Plant deficiency symptoms include yellowing of older leaves between the veins and if prolonged deficiency occurs younger leaves can also be affected and older leaves may be excised (Hochmuth, 2007). Low Mg in forage crops can also lead to a disorder called grass tetany also known as hypomagnesia in grazing animals (Sabreen et al., 2003). Outbreaks of this disorder have been associated with forage crops high in Al (Fontenot et al., 1989). High aluminium (Al^{3+}) concentration in nutrient solution competes with both Ca^{2+} and Mg^{2+} for binding site on the cell wall, plasma membrane, enzymes and membrane transporters, which interrupts the uptake and translocation of these latter nutrients (Lazarević et al., 2011). A survey in the Sandveld showed that most soils were acidic and had a pH of 4-5. At such a low pH it is important to implement a balanced nutrient programme that is frequently applied to prevent Al toxicity and increase nutrient availability (Knight et al., 2011).

Different reactions have been found for yield and quality characteristics in potato tubers with increasing Mg fertilisation. Studies showed that the yield maximum was achieved at a moderate Mg level while some favourable and unfavourable traits increased with higher fertilisation, these included free amino acids, firmness, crude fat and crude protein (Klein et al., 1981, 1982; Evans and Mondy, 1984). However, an increase in glycoalkaloids, which is an undesirable characteristic in potato tubers also increased (Evans and Mondy, 1984). A later study disputed the finding of an increase of glycoalkaloids with increase in Mg (Rogozińska and Wojdya, 1999). The role that Mg plays on improving keeping quality has been studied by numerous researchers and they concluded that it had a positive effect on restricting natural losses (Rogozińska and Jaworski, 2001; Wszelaczynska and Poberezny, 2011). In contrast to Mg, an increase in N increases susceptibility to post harvest diseases and delays skin set during the vegetative stage. Numerous studies have highlighted the negative effects of increased N on storage life in potatoes (Dean and Thornton, 1992; Wilson et al., 2009; Wszelaczynska and Poberezny, 2011).

Magnesium is also very important for humans since many disorders have been associated with low Mg intakes. Considerable less studies have been done on Mg and it is regarded as the “orphan nutrient” compared to Ca. In the USA Ca intake compared to Mg intake from food has increased over time according to an analysis of the USDA surveys (Rosanoff, 2010). Increasing Ca and Mg in potatoes through plant breeding to the extent that it is a large source for humans is unrealistic. A more appropriate exploration would be to look at the different concentrations of Ca and Mg to control physiological disorders and diseases in potatoes (Brown et al., 2012).

2.6 QUALITY CHARACTERISTICS OF SEED- AND WARE POTATOES

Quality is defined as "the sum of characteristics which a product must have so as to meet the stated or implicit needs of the consumer" (Schuphan, 1961). Quality of fruit and vegetable products has also been categorised into six categories including market-, utilisation-, sensory-, ecological-, imaginary-, nutritional and health value (Huyskens-Keil and Schreiner, 2003).

The quality of seed potatoes is influenced by its genetic composition, health standards, physical- and physiological criteria. Genetic composition determines whether seed are true to type or not, whilst the physical criteria include size, number of eyes, malformations and skin abrasions. Similarly, physiological criteria include dormancy, actual or potential sprout number and healthy growth. Health standards also determine quality and it includes tuber-borne diseases. Factors determining yield often affect seed quality such as size, physiological age, number of sprouts per seed tuber and the portion of sprouts that mature into main stems. Physiological age includes characteristics such as dormancy and senescence, which is very important for seed quality. The following factors influence the physiological age namely cultivar, tuber size, storage conditions, seed treatment, growing conditions, agronomic practices and tuber maturity at harvest (Struik and Wiersema, 1999).

Specific gravity have long been used to give an estimation of the dry matter (DM) and starch in a non-destructive way (Burton, 1989). Although each cultivar has a maximum potential SG, it is a genetic trait that can only find complete expression under long growing seasons with warm day and cool night temperatures, sufficient water and optimal nutrients (Smith et al., 1997). Excess N fertilisation will also decrease SG since it will promote vegetative growth. Potassium plays an important role in various physiological processes that effect carbohydrate metabolism and concentration and subsequently the SG. These include water relations, photosynthesis, photosynthate transport and enzyme activation (Römheld and Kirkby, 2010). Starch synthase is an enzyme that catalyses glucose to starch and this enzymes activity depends on univalent cations, especially K^+ (Nitsos and Evans, 1969). Phloem loading, glutamine and sucrose uptake into sieve vessels are enhanced with K^+ (Bel and Erven, 1979). Within a certain cultivar the tubers containing a high SG are associated with numerous large starch granules and the opposite is true for tubers with a low SG (Reeve, 1967). Redulla and Davenport (2002) found a negative correlation between SG and K^+ in the soil.

Organic acids like citric acid play an important role in keeping quality. A positive correlation has been found between malic- and citric acid with non-enzymatic browning of tubers (Mondy, 1982). Smith claimed that the concentration of nutrients in tubers can be associated with a number of quality characteristics (Smith, 1977). Higher Ca rates given during growth lead to higher uptake of Ca by tubers and decreased accumulation of organic acid and sugars, which lead to increased keeping quality (Venter, 1989). Controlling the metabolism through reduction in physiological activity will help to maintain the quality of both seed- and ware potatoes, which could be achieved by low temperatures or sprouting inhibitors (Struik and Wiersema, 1999).

The quality of ware potatoes is affected by the %DM it contains and the composition of the tuber. Potato varieties that are used commercially varies between 18-26% in DM content (Burton, 1989). Dry matter includes carbohydrates, protein, vitamins, allergens, anti-nutritionals, glycoalkaloids, other metabolites and nutrients. Starch is the most important part of tuber DM content (Vreugdenhil et al., 2007). Patatin is the most abundant protein in tubers and protein crystals usually dissipates during storage (Harris, 1992). The sugars of importance in tubers are sucrose, fructose and glucose (Smith, 1977; Venter, 1989). A study showed that plants that received the lowest Ca had higher sugar accumulation in the tubers and had the lowest keeping quality (Venter, 1989). The two factors that had the biggest effect on sugar accumulation during storage were temperature and cultivar (Venter, 1989). Stored ware potatoes should not be allowed to wilt and fresh mass loss should not exceed 5% according to Harris (1992) and Burton

(1982) and Toivonen (2011) found that at 7% water loss tubers become unmarketable. Physiological disorders such as hollow heart and IBS decreases the quality of fresh potatoes because of its appearance and it might reduce sugar accumulation. The quality of seed potatoes are not affected by hollow heart directly but because hollow heart tubers mostly occur under stress conditions it might influence physiological age (Bussan, 2007).

2.7 STORAGE LOSS

Tuber loss during storage can be separated into two groups namely the quantitative losses and the qualitative loss. The quantitative loss is the mass loss that occurs because of respiration, evaporation and sprouting. Qualitative loss do not affect the mass of the tuber, but loss of specific components that decrease the quality of the tubers, for example SG, DM, organic acids, vitamin, carbohydrates, N compounds and darkening of flesh (Lisinska and Leszczynski, 1989).

There are three variables that determine storage losses namely the cultivar, storage conditions and storage duration. Percentage mass loss and decrease in quality are often used to define storage loss although they cannot always be separated (Harris, 1992). A study showed that K applied with S resulted in potatoes with lower % mass loss after four weeks of storage at room temperature (Moinuddin and Umar, 2004). Storage loss is influenced by respiration, damage due to variable temperature extremes, sprouting, evaporation, disease, and change in chemical and physical properties. The length of storage has an impact on tuber texture because prolonged storage increases respiration, leading to diminishing starch content (Smith, 1977). Fluctuation in storage temperature can cause a “respiration burst”. The most rapid increase was found when tubers were moved from 2 to 8 °C compared to moving it from 8 to 2°C (Burton, 1974). Mature tubers have a decrease in respiration post-harvest and increases when the dormancy has ended (Schippers, 1977). The following factors should be controlled during storage, namely temperature, air composition and distribution, ventilation rate, sprout growth and diseases. Storage temperature range for seed potatoes are 3-4 °C and ware potatoes are 4-5 °C (Veerman and Wustman, 2005).

Sprouting of tubers is accelerated under higher RH at temperatures of 18-22 °C and a high RH can also cause branched sprouts with an increased number of side roots. Low oxygen in the air around the tubers will also increase sprouting, but can also lead to decay of tubers (Lisinska and Leszczynski, 1989). The length of the tuber dormancy period correlates inversely with storage temperature ranging from 3 to 25 °C (Burton, 1989). Increasing CO_2 concentration up to 8%, leads to a concomitant increases in sprouting of tubers, but sprouting is retarded at higher concentrations (Burton, 1958). Combined treatments of CO_2 and O_2 can modify sugar content, lower abscisic acid (ABA) levels and the dormancy period (Coleman, 1998). To prevent low temperature injury in tubers it is recommended that it be stored above 3 °C. Temperatures of 31 °C is considered the maximum for sprouting to still occur while at temperatures above 40 °C tubers die (Lisinska and Leszczynski, 1989).

Potato tuber mass consists of 70-80% water, while the outer layer skin (phellem) acts as a barrier to prevent water loss through evaporation. The rate of water loss depends on the vapour pressure deficit (VPD). Free water in tubers is situated within the cell wall matrix and it is postulated that the RH is around 100%. Evaporation loss is responsible for 98% of the water loss in tubers and the remaining 2% is due to direct diffusion through the lenticels (Burton, 1978). The % mass loss due to respiration is very low compared to evaporation (0.5-1%) for a storage period of six months (Davis and Smith, 1965). High temperatures increase respiration in tuber and can reduce SG while low RH can increase SG because of water loss, but there is a risk of pressure bruising during shrinkage (Smith et al., 1997). Any physical damage to the skin of tubers increases the water loss of tubers. Even a small amount of skinning (<5%), can double the amount of water loss in tubers (Navarre and Pavek, 2014). It has been shown that by removing the tuber skin the rate of evaporation increased by 300 to 500 times (Burton, 1989). Wounds that occur because of skinning readily occur unless the periderm matured, which causes the skin to set and be resistant to skinning. If the periderm is well developed and intact with its suberin biopolymer it serves as the primary defence against pathogens, insects, water loss and physical penetration into potato tubers (Lulai, 2001). Before the periderm develops, epidermis exists temporarily on young tubers with a diameter of 1 cm or less. The tuber periderm consists of three layers namely phellem (suberized cells), phellogen (cork cambium) and phelloderm and forms of epidermal tissue (Vreugdenhil et al., 2007). The phellem is the part of the periderm that has been referred to as the skin and skinning is the process where the phellem is removed from the tissue below it (Lulai and Freeman, 2001).

Vine killing or destruction still remains the standard procedure for promoting periderm maturation and the development of skinning resistance, in general about 3 weeks are required for development after vine kill (Lulai and Orr, 1993). Low RH increased the maturation of the periderm of tubers under a controlled environment (Lulai and Orr, 1993). The phellogen was identified as the tissue directly involved in skinning injury and skinning resistance increased with declining phellogen activity (Lulai and Freeman, 2001). A uniform method for measuring skin-set and thus resistance to skinning injury is vital to evaluate the value of cultural practices planned to increase skin-set development, but none has been adopted (Vreugdenhil et al., 2007). No correlation between periderm maturation and skin-set development with phellem thickness, mass of the phellem or phellem histology has been found (Lulai and Orr, 1993). Tuber quality characteristics that may decrease the incidence of mechanical damage include size, starch, firmness, tuber physiological age and cell characteristics such as size, cell wall strength, periderm characteristics (Venter, 1989). Tuber shape is mostly under genetic control but it can be influenced by soil texture and water stress (Harris, 1992).

2.8 HOLLOW HEART AND INTERNAL BROWN SPOT

Brown centre is characterised by a brown discoloration of pith tissue that is firm and small near the centre of the tuber. Susceptibility of tubers to brown centre is highest from the stage of tuber initiation until the stage that tubers weigh about 56 g (Thornton, 2001). During tuber initiation cool soil temperature of about 10-15 ℃ are reported to induce brown centre (Van Denburgh et al., 1980). The discoloration in the tuber is caused by the damage to the cell membrane and organelles as well as necrosis of the cells affected (Van Denburgh et al., 1986). It is postulated that brown centre is a precursor for hollow heart and that it and hollow heart are two different phases of the same disorder but can occur independently (Hiller et al., 1985; Hiller and Thornton, 2008).

Hollow heart is characterised by a cavity in the middle of the tuber, usually star-shaped but it can also be lens or irregularly shaped, its frequency may increase with environmental or nutritional stress (Levitt, 1942; Rex and Mazza, 1989). The hollow heart cavity may develop a suberin lining giving the structure a dark brown or tan colour (Dean et al., 1977). Two types of hollow heart can occur namely stem-end hollow heart and bud-end hollow heart. The first is formed in the region of the stem end of tubers and the latter in the bud end. Stem-end hollow heart develops when a tuber is affected with brown centre and starts to grow rapidly, the perimedullary region may then outgrow the pith region causing a cavity to form due to a split or tear in tissue (Rex and Mazza, 1989). Stem-end hollow heart mostly form during tuber initiation and is associated with brown centre (Levitt, 1942) while bud-end hollow heart is usually initiated during tuber bulking and is not associated with brown centre (Thornton, 2001). It is mostly caused by a stop in tuber growth because of water or nutritional stress in the lateral part of the season. Larger tubers have an tendency to have higher occurrence of hollow heart and other internal defects (Jansky and Thompson, 1990; Nelson, 1979), but in small tubers it can also occur during rapid tuber growth (Hiller et al., 1985). A study done using electron microbe and neutron activation analysis showed that the Ca gradient from the stem end to the bud end were significantly higher in tubers containing hollow heart (Arteca et al., 1980). Black heart occurs in the middle of the pith tissue as a black melanin discoloration. Similarly to hollow heart, in black heart a cavity can form but instead of a wounded periderm a grey or black layer forms known as “cat’s eye”’ (Strand, 2006). It is caused by an O_2 deficiency that limits respiration inside the tuber tissue (Davis, 1926). In an extreme anaerobic environment external symptoms of blackheart can initially occur as moist, discoloured areas that can be purple at first, subsequently turning brown or black as it progresses (Dykstra, 1941). In the field high temperature and waterlogged conditions can cause O_2 deficiencies and thus black heart. During storage, extreme temperatures or inadequate ventilation can cause O_2 deficiencies (Navarre and Pavek, 2014). Seed tubers affected by black heart should not be planted because of an increase in occurrence in soft rot and poor emergence (Wale et al., 2008).

Tubers with non-pathogenic necrosis have varying names including IBS, internal brown fleck (IBF), internal browning, internal heat necrosis, internal rust spot, chocolate spot and physiological internal necrosis (Hiller et al., 1985). The names refer to the same internal disorder or disorders that are indistinguishable (Navarre and Pavek, 2014). The term IBS is used in western USA while in eastern USA the term internal heat necrosis (IHN) is used. In Europe the term internal rust spot is used (Navarre and Pavek, 2014), while in South Africa the term IBS is mostly used, referral to IBF occurs (Kempen, 2012). Internal heat necrosis is not necessarily caused by high temperatures, but rather because of a variation of environmental conditions (Sterrett, 1991).

In IBS, internal heat necrosis and hollow heart, there are normally no external symptoms on the tubers, stems, flowers or leaves. It is well established that these physiological disorders are linked to Ca deficiencies (Palta, 1996). Initially it was thought that the cause for IBS was due to deficient P (Van der Plank, 1930), but it was later proposed that the likely cause of IBS was related to a Ca deficiency and subsequent damage to cell walls (Combrink and Hammes, 1972). Internal brown spot has been associated with localized Ca deficiencies, which mean that Ca is restricted in the tuber. This causes loss of membrane integrity and may be accompanied by oxidative damage, which can lead to cell death when it is severe (Davies, 1998). Davies also found that resistant cultivars have higher activity of antioxidants than susceptible cultivars. When Ca availability or fertility in the soil is low and the soil temperature is high IBS increases in incidence (Navarre and Pavek, 2014).

When high day temperatures and low night temperatures occur with low soil moisture early in the season IBS increases in severity and frequency (Sterrett, 1991). Sandy soils have low cation exchange capacity (CEC) and very good heat conductance and IBS might be found more regularly on these soils (O'Brien and Rich, 1976). IBS symptoms include spongy and suberised reddish-brown or rust-coloured necrotic parenchyma cells that have inadequate levels of starch. Cell walls are misshapen, suberised and thickened and vacuoles contain dark stained granules (Baruzzini et al., 1989). In IBS the spot can occur anywhere inside the tuber, but it mostly occurs on the inside of the vascular ring.

Care should be taken not to confuse IBS with viruses or other pathogenic diseases including non-pathogenic vascular discoloration (Kempen, 2012). Internal brown spot can start to develop soon after tuber initiation has taken place (Olsen et al., 1996). Periods of rapid growth of tubers are also linked to IBS development (Hiller et al., 1985). Necrotic spots initially occur at the bud end of the tuber and in due time it spreads through the tuber and the colour intensifies (Sterrett, 1991). Internal brown spot differs from IHN as it can occur in any part of the tilled ridge while internal heat necrosis can only occur at the soil surface (Hiller et al., 1985). Brown centre and IBS differ from each other because in brown centre the necrotic spots are mostly in the centre or pith of the tuber (Navarre and Pavek, 2014).

2.9 AGRONOMIC PRACTICES AFFECTING TUBER QUALITY

The two classified categories for production variables are the non-controllable and partially or completely controllable variables by the producer that determine the yield. Duration of growing season, air temperature, day length, wind and soil characteristics are reserved under non-controllable parameters. The soil temperature and pest status are classified as partly controllable. The controllable category includes cultivar, seed quality, planting density, soil moisture content, fertilisation, crop rotation, speediness of farming operations, vine destruction, handling and transport and storage conditions (Smith et al., 1997).

When the plant spacing is wide it promotes the growth of larger tubers, which subsequently causes the incidence of hollow heart to increase (Rex et al., 1987). Hollow heart increase when high rates of N are given late in the season (Wilson et al., 2009) or if N is applied during tuber initiation (Hiller and Thornton, 1993). There is a trend that K fertilisation decreases hollow heart (Panique et al., 1997). Non-periderm Ca concentration of 100 µg g^{-1} tuber dry mass or smaller has greater occurrence of hollow heart (Kleinhenz et al., 1999). A decrease in IBS was found in tubers with a Ca content of 100 to 250 µg g^{-1}. Several studies have shown that during tuber bulking a Ca application can increase the Ca concentration in the tuber (Gunter et al., 2000; Karlsson et al., 2006; Ozgen et al., 2006). Cultural practises used to decrease hollow heart incudes uniform plant stand, reduced plant stress and steady plant and tuber growth rates (Hiller et al., 1985; Navarre and Pavek, 2014). Good plant stands can be achieved by planting at the proper soil depth, using large seeds and planting at the correct spacing. Reduced plant stress and steady growth can be achieved by avoiding over irrigating, over fertigation and maintaining adequate soil moisture and soil fertility. High yields are obtained when evapotranspiration losses are replaced every day or every second day. For optimum yield the available soil water content should not be allowed to drop below 30 to 50%. Water stress during the yield formation may result in cracking and black heart. An increase in DM content can be achieved with water stress during ripening, but it has been shown that frequent irrigation reduces the occurrence of tuber malformations (Doorenbos and Kassam, 1979). Yield is greatest affected when there is a water deficit during stolon formation, tuber initiation and yield formation. Varieties with less tubers might be less sensitive to a water shortage than varieties with plenty of tubers (Doorenbos and Kassam, 1979). Potatoes have a very short root system and uptake will vary depending on soil structure and texture (Doorenbos and Kassam, 1979). Mulching and a closed canopy can help to keep the soil moisture at a desirable level. Under certain circumstances it may be necessary to delay planting to avoid cool soil temperature during tuber initiation, which will decrease the incidence of hollow heart as well as IBS because of decrease of tuber size (Navarre and Pavek, 2014).

In areas with high temperatures it is important to mature the crop before the soil temperature becomes too high, which will increase the incidence of IBS. Haulm and leaf destruction is used to reduce skinning at harvest, shrinkage during storage, slow disease development, reduced bruising during harvest and lastly to weaken stolon attachment and above ground biomass to increase harvest productivity (Ronald, 2005). Haulm and leaf destruction can lead to reduced yield, size and SG. It also compromises photosynthesis, but tubers are still able to absorb water that can cause a decrease in DM (Harris, 1992). It is important to supplement sandy soils and soils low in Ca with Ca close to the tuber region to improve Ca uptake and content in the tubers (Palta, 2010).

In acidic soils such as those found in the Sandveld leaching may be decreased by adding lime to increase the soil pH, because many elements form more soluble compounds when the soil pH is higher than 6 (Taiz and Zeiger, 2010). It is better to fertilise with gypsum than with lime when the soil pH is already correct since gypsum is about 200 times more soluble than lime (Fischer, 2011).

The farmers of the Sandveld also have problems with nematodes when the soil pH is high. Nematodes interchange different ions through their cuticle to regulate their osmotic potential (Castro and Thomason, 1971). It has been suggested that a low pH can cause increased ion concentrations in the soil water which may cause problems for nematodes to regulate their water status (Baath et al., 1980). High pH soils tend to be more susceptible to common scab (*Streptomyces scabies)* infections ("Yara Crop Nutrition," n.d.) and keeping the soil pH below 5.5 will slow down disease development (Knight et al., 2011; Denner et al., 2012). Average SG of tubers are not significantly affected by soil pH of 4.9-7.6 but high concentrations of Cl decreases SG and DM of potatoes (Smith and Nash, 1941). The transfer of starch from leaves to the tubers are inhibited by Cl (Finck, 1982) thus the decrease of SG and DM.

2. 10 References

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CHAPTER 3

Comparing potato tuber quality characteristics over different seasons and sizes

3.1 Abstract

Potatoes vary in keeping quality and these differences can partially be attributed to cultivation in different environments. Seasonal differences in quality do occur and the weight loss dynamics vary according to tuber sizes. Some quality characteristics include skin strength, physiological status, specific gravity (SG) and absence of physiological disorders. This study was conducted to help understand the variation in quality characteristics of different sized tubers that influence the keeping quality of potatoes produced under different environments. Sixty one potato samples were assessed over two years during different seasons and in different fields. Tubers were sampled from ten different producers and phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and boron (B) content were analysed. Skin strength and SG were also measured. The cultivar selected for this study was Sifra and it has an early skin set, meaning that harvest can commence early with reduced skinning. Specific gravity was highest in medium tubers while large tubers had significantly lower Ca levels. Different size tubers did significantly differ in Mg concentration. Calcium was markedly higher in autumn than in spring, but the Ca values in winter and summer did not differ significantly from that in autumn or spring. The Ca:Mg ratio followed the same pattern as calcium regarding the size of the tubers and the seasonal changes. Thus under most conditions Ca fertilisation should have an marked effect on the Ca:Mg ratio compared to Mg fertilisation.

Keywords: Quality, seasons, sizes, SG, Ca:Mg

3.2 Introduction

Potato (*Solanum tuberosom* L) is one of the most important crops currently under production and its tubers is of high nutritional value (Millam, 2007). High levels of starch occur in the tuber as well as fibre, protein, vitamins and minerals that humans need for growth and good health (Storey and Davies, 1992). Potato is a cool-season crop, but high yields can be obtained in warmer regions. Potatoes are short-day adapted for tuberization, but most modern cultivars do not have a strict need for short days in order to form tubers (Navarre and Pavek, 2014). Potatoes consist of cells that is metabolically reactive to environmental conditions, they are hydrated, highly respiring and mostly parenchymatous cells (Peterson et al., 1985). In terms of production, potato is the fourth largest farmed crop after wheat (*Triticum aestivum*), rice (*Oryza sativa*) and corn (*Zea mays)* (Fabeiro et al., 2001). In the Western Cape dry, hot summers occur creating a challenge in terms of producing high volume quality potatoes. Heat waves during tuber bulking can decrease tuber quality and inhibit crop growth (UNECE, 2014).

Specific gravity (SG) is used as a standard index in the USA, Holland and RSA for potato quality (Lugt, 1961; Niederwieser and Raan, 2017), although higher SG does not necessarily correlate with better keeping quality (Venter, 1989). High SGs are important in the processing industry since they produce more product from the same amount of raw material and the final product is more rigid, crisp and contains less oil (Storey and Davies, 1992). The potato cultivar Sifra has foliage that develops vigorously and accumulates DM content of 19.7%, starch levels up to 13.9% and an SG of 1.077 (“HZPC,” 2016). For potatoes to qualify for processing it must contain a SG ≥1.075 (“Fact sheet: Internal quality,” 2016). Within a particular cultivar the tubers containing a high SG are associated with numerous large starch granules and the opposite is true for tubers with a low SG (Reeve, 1967). Each cultivar has a maximum potential SG and thus it is a genetic trait, which expresses maximally only under long growing seasons with warm day- and cool night temperatures with sufficient water and nutrients (Smith et al., 1997).

Nutrients present in dicotyledon cell walls include Ca, K, Na, Fe, Mg, Si, Zn and B (Welch and Shuman, 1995; Epstein, 1999). Potassium plays an important role in various physiological processes that affect carbohydrate metabolism and concentration and subsequently the SG. The postharvest usage of tubers is influenced by K fertilisation more than that of N or P. Tuber size in general are increased with K fertilisation causing an increase of large tubers relative to small ones (Martin-Prével, 1989). High K levels promote larger size tubers and cause an increase in water accumulation in cells resulting in lower dry matter (DM) and thus lower SG (Perrenoud, 1993). Potassium roles in plants include water relations, photosynthesis, photosynthate transport and enzyme activation (Römheld and Kirkby, 2010). Starch synthase is an enzyme that catalyses glucose to starch and this enzyme's activity depends on univalent cations, especially K^+ (Nitsos and Evans, 1969). Phloem loading and particularly glutamine and sucrose uptake into sieve vessels are enhanced with higher K^+ (Bel and Erven, 1979).

Calcium is important in maintaining cell wall structure and membrane permeability by binding with pectic acid to form cross links (Palta, 1996). The main mechanism for Ca transport in plants is transpiration (Busse and Palta, 2006). Calcium deficiencies are linked to several physiological disorders in plants and are normally associated with organs which have a lower transpiration rates such as potato tubers (Bangerth, 1979). Calcium is considered immobile constraining translocation in the phloem thus transportation can only occur via the xylem and only unidirectionally transport can occur (White and Broadley, 2003).

Potato is one of the commercially produced vegetables that can be considered intolerant to a Mg deficiency (Bear et al., 1951; Hochmuth, 2007). Inadequate Mg will also affect the carbon (C) assimilation and the transformation of energy (Barker and Pilbeam, 2015). Studies showed a yield maximum at moderate Mg levels (<50 kg ha^{-1}) while some favourable traits increased with higher Mg fertilisation; these include free amino acids, firmness, crude fat and crude protein (Klein et al., 1981, 1982; Evans and Mondy, 1984; Allison et al., 2001).

When numerous cells are affected by internal brown spot (IBS) the cells become spongy, suberised and low in starch (Baruzzini et al., 1989). In IBS, spots can occur anywhere inside the tuber, but mostly on the inside of the vascular ring. Periods of rapid growth of tubers are also linked to IBS development (Hiller et al., 1985). Internal brown spot and hollow heart are both at least partly caused by nutritional stress. A decrease in IBS was found in tubers with a Ca content of 100 to 250 µg g^{-1} dry mass.

Hollow heart (HH) is identified by a cavity in the middle of the tuber - usually star-shaped (Rex and Mazza, 1989). Two types of HH occur, namely stem-end and bud-end HH. Stem-end HH mostly form during tuber initiation and is associated with brown centre (BC) (Levitt, 1942) while bud-end HH is usually initiated during tuber bulking and is not associated with brown centre (Thornton, 2001). Hollow heart increases when high rates of N are given late in the season (Wilson et al., 2009) or if N is applied during tuber initiation (Hiller and Thornton, 1993). Non-periderm Ca concentration of 100 µg g^{-1} DW or smaller has greater occurrence of HH (Kleinhenz et al., 1999).

Haulm and leaf destruction is used to reduce skinning, shrinkage, slow down disease development, reduce bruising during harvest and lastly to weaken stolon attachment and above ground biomass to increase harvest productivity (Ronald, 2005). Numerous studies have highlighted the positive role that Mg plays in improving potato keeping quality and there is widespread consensus that it limits natural losses. In contrast to Mg, N increases susceptibility to post harvest diseases and delays skin set during vegetation stage (Rogozińska and Jaworski, 2001; Wszelaczynska and Poberezny, 2011). Sifra has an early skin set meaning that harvest can commence early with reduced skinning (“HZPC,” 2016).

The quality of seed potatoes is influenced by its genetic composition, seed health, physical- and physiological criteria (Struik and Wiersema, 1999). Percentage weight loss and decrease in quality are often used independently to define storage loss although they are really inseparable (Harris, 1992). Evaporation loss is responsible for 98% of the water loss in tubers and the remaining 2% is due to direct diffusion through the lenticels (Burton, 1978). Sprouting of tubers is accelerated under higher humidity at temperature of 18-22 °C and high humidity can also cause branched sprouts with an increased number of side roots. Low O_2 in the air around the tubers will also increase sprouting, but can also lead to decay of tubers (Lisinska and Leszczynski, 1989). The objective of this study was to investigate differences in quality characteristics between seasons and sizes in Sifra.

3.3 Materials and Methods

3.3.1 *Description of Sampling Area*

Sampling was done in the Sandveld and Ceres, more specifically the Kouebokkeveld area throughout 2016 and until June 2017. Both are part of the Western Cape and thus have a Mediterranean climate that is characterised by dry, hot summers with low rainfall. In summer (December-February) growth is regularly inhibited by high temperature while in winter (June-August) photosynthesis limits growth due to low solar radiation intensities (Franke et al., 2011). The Sandveld are close to the South Atlantic Ocean and cool see breezes occur during the day while the Kouebokkeveld are not affected by sea breeze. Strong winds occur in both these areas that can cause damage to plants. The predominant wind in the summer is South-east. Summers have long days and short nights, while short days and long nights occur in winter. The day length and temperature start to decrease in autumn (March-May). In winter cold temperatures and high rainfall occur and in the Kouebokkeveld snowfall and frost are common during winter. The predominant wind in winter is South-western. In the Sandveld the long term annual rainfall is about 300 mm annually (Franke et al., 2011). The rainfall during the main potato growing season is 127 mm for the Sandveld (June) and 107 for the Kouebokkeveld (October) (Van der Waals et al., 2016). During spring (September-November) the day length and temperature begins to increase. The periods described above as winter, spring, summer and autumn were used as the Season treatment in this study.

Both the Sandveld and the Kouebokkeveld contains sandy soils with varying pH, low clay and low C content. Some of these soils are highly saline and high sodium content is also common. Saline soil is classified have an electrical conductivity of a saturated soil extract (EC_e)>4 dS m^{-1}, exchangeable sodium percentage (ESP)<15% and sodic soil EC_e<4 dS m^{-1}, ESP>15% (Richards, 1954). The cation exchange capacity (CEC) of the soils sampled ranged between 1-6 $cmol^{+}.kg^{-1}$ and the ESP values ranged from 1-38%.

The electrical conductivity (EC) of the irrigation water varied from 0.03 dS m^{-1} to 2.18 dS m^{-1}, the irrigation water of the Sandveld having much higher EC as well as higher sodium absorption ratio (SAR) as expected since it is very close to the sea. No yield loss occurs for potatoes with irrigation water of 1.1 $dS.m^{-1}$ but at 1.7 $dS.m^{-1}$ a 10% loss can be expected and at 3.9 $dS.m^{-1}$ a 50% yield loss was reported (Ayers, 1975).

In the Sandveld planting can occur throughout the year, but most are planted in February and June. Planting in the Kouebokkeveld (Op Die Berg) mostly occurs in September to November. Samples taken from the Kouebokkeveld were planted in double rows with sprinkler irrigation while in the Sandveld most were planted in double rows and all under pivot irrigation.

3.3.2 Data collected

Four to seven plants were sampled to obtain at least 51 undamaged tubers. With each tuber sample a soil and water sample were also taken and it was sent to the Western Cape department of Agriculture's soil, water and plant laboratory at Elsenburg for analyses. Soil samples were taken 300 mm deep, near the tubers on the ridge and between rows by using an auger while water samples were taken at the nearest water source, usually at the pivot. The soil analyses were adapted from Non-Affiliated Soil Analysis Work Committee (1990), soil pHs were done in KCl and P levels were assessed by the Olsen method (Olsen, 1954). Water analyses for the different elements were done by ICP (Inductively Coupled Plasma Spectrometer) and chlorides and bicarbonates were determined by titration. Tuber analyses were also done by ICP and recorded on DW basis according to Palic et al., (1998).

The day after sampling tubers were washed with a diluted Sporekill (didecyldimethyl ammonium chloride) concentration of 0.02% (v/v). All soil debris and excess materials were removed. Sorting occurred by removing any damaged, green or disease infected tubers from the sample set. Any tubers <26 mm in diameter were removed from the sample set. Tubers were then classified as large, medium or small based on the sample set. Tubers were then left to dry on white paper towels.

The following process was repeated for large, medium and small tubers and for storage at 25°C and 5°C. Three tubers were weighed and skin-set was tested by using the farmers' method by rubbing the skin with the thumb (Kabira and Lemaga, 2003). Each tuber was given a score out of five for each time the skin was removed by a rub, they were then sent to Elsenburg for analyses of Ca, B, Na, K, P and Mg content. Three tubers were weighed on day one, and physiological disorders HH and IBS were recorded by cutting the tubers into pieces of eight and giving it a rating out of 8. Thus, the distribution and not the intensity was measured.

The SG of three tubers per sample was measured on day one. The water displacement method was used (Tabatabaeefar, 2002). Tubers were submerged into a known water volume and the volume water displaced is measured. Specific gravity was than determined by dividing tuber mass in grams by the displaced water volume (mm). Tubers stored as ware potatoes were stored at 25°C and weighed at day 1, 7, 14, 28 and 42. Storage at 25°C was done in a dark ventilated room, but without controlled air humidity or temperature control. Tubers stored as seed potatoes were stored at 5°C and weighed at day 1, 28 and 42. Storage at 5°C was done in a ventilated dark room, but without controlled air humidity or light. Percentage mass loss was determined after storage on day 42. Firmness was determined at the end of the storage period by hand and giving it an index value from one to five, for statistical purposes three was left out, while one and two were classified as soft and four and five as firm.

Sprouts were classified when growth were > 4mm although 2-3 mm has been used in the past for criteria for the end of dormancy (Van Ittersum, 1992). The purpose of this length of sprouting is to ensute that continual growth has occurred.

3.4 Statistics

Two-way analysis of variance (ANOVA) was done to investigate the relationship between different quality characteristics over different seasons, sizes and the interaction between them. The significance level denoted as alpha was selected as 0.05. Test for normality were also done on the data set.

3.5 Results and Discussion

No significant difference was found for the mass of the sampled tubers between the different seasons (Table 3.1). For the different storage methods both had significant differences in percentage mass loss for different sizes. The small tubers had the most pronounced loss followed by the medium and then large tubers. Although the small tubers had highest percentage mass loss their rate of mass loss (g d^{-1}) were the smallest followed by medium and then large as expected since large tubers have more mass to lose but their overall mass is least affected.

Table 3.1. P values for two-way analysis of variance (ANOVA) for the dependent variable (source) compared to the two independent variables (season and size) and the interaction between them. The alpha was selected at 5% for the test.

Source	Season	Size	Season x Size
Mass	0.7144	<0.001	0.6744
Skinning	0.3655	0.0589	0.8363
IBS	0.1292	0.0182	0.5208
HH	0.6857	0.5994	0.4484
% Mass Loss 5	0.5724	<0.001	0.1149
% Mass Loss 25	0.0763	<0.001	0.4555
SG 5	0.0276	0.003	0.3199
SG 25	0.2003	<0.001	0.5922
SG5 Sprouting	0.3487	0.0202	0.3315
SG 25 Sprouting	0.2136	0.0077	0.3175
SG 5 Firm	0.46	0.0228	0.1457
SG 25 Firm	0.1393	0.0085	0.2479
SG 5 Soft	0.3131	0.3863	0.1353
SG 25 Soft	0.5814	0.0054	0.9699
Tuber P	0.0134	0.4146	0.0564
Tuber K	0.0042	0.6646	0.0004

Tuber Ca	0.0038	<0.001	0.4044
Tuber Mg	0.0245	0.2446	0.1656
Tuber Na	0.0649	0.0011	0.9699
Tuber B	0.7533	0.0305	0.0799
Tuber Ca: Mg	0.0022	<0.001	0.5865

Potato physiological maturity can be defined as the moment the maximum SG is reached during the growing season (Myhre, 1959). Variation of SG can be expected within a field and even among tubers grown on the same plant (Love and Pavek, 1991). High temperature increases respiration in tuber and can reduce SG, while low RH can increase SG because of water loss but there is a risk of pressure bruising during shrinkage (Smith et al., 1997).

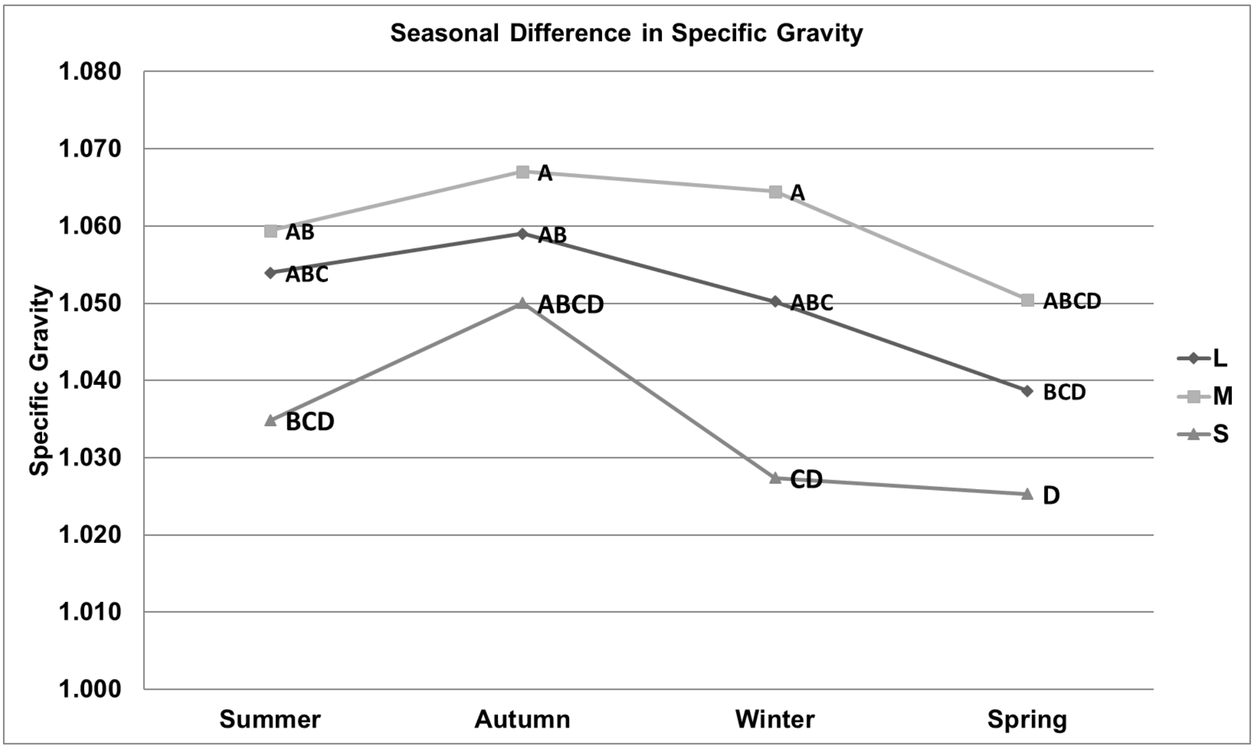

Figure 3.1. Mean specific gravity (SG) for storage at 5°C and 25°C together over different harvest seasons. The letters indicate the significant difference between the season and size interaction.

No significant difference between seasons occurred for either SG 5°C and SG 25°C, but there was a significant difference between sizes (see Table 3.1). The medium tubers had the highest mean SG and this corroborated the findings of Ifenkwe et al., (1974) who discovered that the maximum percentage DM loss occurs in medium sized tubers. The large tubers had the second largest mean SG and the small tubers had the lowest. The interaction between season and size was not significant for either SG 25°C or SG 5°C. Although there wasn't a significant difference between harvest seasons the mean SG of tubers showed an increase from summer to autumn and decreased through winter and spring (Figure 3.1). The pattern might have been due to alternating colder and longer seasons in winter and shorter seasons in summer being the hottest months. In summer the SG might be lower than in autumn because of the occurrence of heat stress.

Table 3.2. Means with the least significance difference (LSD) for two-way analysis of variance (ANOVA) for the dependent variable (source) compared to the independent variables (season). The alpha was selected at 5% for the test and the letters indicate the significant differences.

Source	Spring	Autumn	Winter	Summer	LSD
SG 25 Sprouting	0.185 (AB)	0.284 (AB)	0 (B)	0.4236 (A)	0.3902
Tuber P	0.40889 (B)	0.45012 (B)	0.52167 (A)	0.47485 (AB)	0.0672
Tuber K	2.525 (A)	2.4907 (A)	3.3667 (A)	2.5545 (B)	0.3704
Tuber Ca	0.0275 (B)	0.049259 (A)	0.046667 (AB)	0.038485 (AB)	0.0197
Tuber Mg	0.141667 (AB)	0.127407 (B)	0.15 (A)	0.131212 (B)	0.0181
Tuber Ca: Mg	0.20001 (B)	0.3922 (A)	0.31944 (AB)	0.29772 (AB)	0.1643

No significant differences between seasons, sizes or interaction between them occurred for % skinning or hollow heart. Low incidence of hollow heart in this study was probably the reason for no significant interaction because previous studies have shown large tubers tend to have higher HH incidence (Jansky and Thompson, 1990; Nelson and Thoreson, 1986). Internal brown spot had no significant interaction between season or the interaction between season and size. Significant differences occurred between sizes, large significantly differed from medium and small (Table 3.3). Although literature suggests that in summer months the incidence of IBS is higher, there were no significant differences in this study. Under certain circumstances it may be necessary to delay planting to avoid cool soil temperatures during tuber initiation, which will decrease the incidence of HH as well as IBS because of decrease of tuber size (Navarre and Pavek, 2014).

Significant differences only occurred for different sizes for sprouting at 5 °C and 25 °C storage (Table 3.3). Firmness of tubers differed significantly between tuber sizes but not seasons. Small tubers were significantly less firm than large and medium. Soft tubers were significantly different only for 25 °C storage, with medium tubers showing the most pronounced reduction in firmness. Nutrients P, K, Ca and Mg concentrations differed significantly between seasons while levels of Na and B were unchanged. Calcium, Na and B differed significantly in the different tuber sizes while P, K and Mg were not correlated to size. Only K had a significant season and size interaction, the Ca:Mg ratio in the tubers differed significantly between seasons and sizes. The tubers harvested in winter had significantly higher Mg than those harvested in summer and autumn, but not spring. Calcium and Ca:Mg ratio were significantly higher in autumn than in spring, but winter and summer did not differ significantly from autumn or spring. Large tubers had markedly lower Ca levels and Ca:Mg ratio, followed by medium and then small, the latter having the highest Ca concentration and Ca:Mg ratio.

Table 3.3. Means with the least significance difference (LSD) for two-way analysis of variance (ANOVA) for the dependent variable (source) compared to the independent variables (size). The alpha was selected at 5% for the test and the letters indicate the significant differences.

Source	Large	Medium	Small	LSD
Mass	192.194 (A)	117.256 (B)	56.273 (C)	12.737
Skinning	0.45892 (B)	0.54235 (A)	0.47562 (AB)	0.0725
IBS	0.011558 (A)	0.002808 (B)	0.002192 (B)	0.0072
% Mass Loss 5	4.1417 (B)	4.8696 (A)	5.0075 (A)	0.403
% Mass Loss 25	4.5321 (B)	4.8516 (B)	5.4399 (A)	0.3912
SG 5	1.056096 (A)	1.06075 (A)	1.041635 (B)	0.0113
SG 25	1.049615 (B)	1.061058 (A)	1.037731 (C)	0.0099

SG 5 Sprouting	0.12808 (A)	0.12192 (A)	0.05115 (B)	0.0595
SG 25 Sprouting	0.35885 (A)	0.24385 (B)	0.23654 (B)	0.0851
SG 5 Firm	0.90423 (A)	0.89096 (A)	0.79481 (B)	0.0845
SG 25 Firm	0.84654 (A)	0.87212 (A)	0.73769 (B)	0.0895
SG 25 Soft	0.09538 (B)	0.21077 (A)	0.10846 (B)	0.0754
Tuber Ca	0.036346 (B)	0.040769 (B)	0.048462 (A)	0.0044
Tuber Na	813.69 (C)	922.9 (B)	1024 (A)	109.23
Tuber B	9.8273 (AB)	9.6281 (B)	10.0512 (A)	0.3123
Tuber Ca: Mg	0.28626 (C)	0.32213 (B)	0.3668 (A)	0.0351

3.6 Conclusion

The rate of mass loss for each specific tuber size was constant throughout the storage period. Specific gravity in this study was significantly highest in medium tubers which concur with literature (Ifenkwe, 1974). Autumn harvested tubers had the highest SG. It is widely accepted that low temperature and short days inhibits haulm growth and increases the dry matter acquisition in the tubers (Menzel, 1985). Long growing seasons with warm day and cool night temperatures will lead to higher SG as opposed to a short growing season (Smith et al., 1997). Significantly higher calcium content occurred in autumn than in spring, but winter and summer did not differ significantly from autumn or spring. Day length decreases in autumn and increases in spring thus tuberisation would be expected to occur faster in autumn than spring (Koda et al., 1988). For maximum tuber production the interaction between temperature and photoperiod should be at optimum. Both early and late tuber initiation will cause a shortened tuber growing period (Van Dam et al., 1996). The long tuber growth period in autumn might be the cause for the higher SG and Ca concentrations. The Ca concentration was highest in the small tubers followed by medium and lastly large tubers. The large tubers had the highest incidence of IBS, since Ca deficiencies is the cause of IBS, this result was expected. Different tuber sizes did not have different Mg concentrations and since redistribution of Mg and other nutrients do occur seasonal differences are difficult to explain, but differences in rainfall and soil temperature may be influential. The Ca:Mg ratio followed the total Ca trend in terms of size and seasonal differences and was thus driven by total Ca which is expected since its concentration in the tubers are higher.

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CHAPTER 4

Identifying and using tuber characteristics to predict seed- and ware potato keeping quality

4.1 Abstract

Keeping quality of potatoes is affected by numerous factors including storage conditions, physiological status, periderm properties, cultivar, physiological disorders, environmental conditions and cultural practices. Producing a physiological quality model that can predict the mass loss during storage can be of high economical value. It can also help future research to see the importance of different nutrients in keeping quality. This two-year field study, which assessed a total of 61 samples of a single cultivar, was conducted to establish a tool that would enable the prediction of the keeping quality of seed- and fresh potatoes produced in the Ceres and Sandveld area.Tuber samples were collected from ten different producers and macronutrient [phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg)] and micronutrient [sodium (Na) and boron (B)] contents, were analysed. Skin strength and specific gravity (SG) were also measured and considered in the model. Evidently, the importance of Mg has globally been overlooked and that the balance of Ca:Mg in the tuber is very important in predicting keeping quality.

Key words: Potatoes, physiological quality model, Sifra, Ca:Mg

4.2 Introduction

Cultivated potatoes (*Solanum tuberosum* L.) that are commercially produced today were selected from the *S. brevicaule* that originates from the Andes and Chile regions in South America (Spooner and McLean, 2005). Potatoes equatorial origin caused it to be short-day adapted for tuberization, although most modern cultivars do not have a strict need for short days in order to form tubers (Navarre and Pavek, 2014). The cultivar Sifra was used in this study and it is classified as a short medium to medium long variety containing large round oval tubers (Ćota et al., 2010). Sifra has an early skin set and can be stored for medium long periods in a well ventilated cold room ("HZPC," 2016). The sandy soils under potato cultivation in the Sandveld and Ceres areas cannot obtain substantial yields without high amounts of fertilisers. In the Sandveld average yield amounts to 49.2 ton ha^{-1} (Van der Waals et al., 2016) but much higher yields can and have been obtained (Franke et al., 2011). The minerals provided by fertilisers also play a big role in determining the quality of the product.

For instance, Ca increases disease resistance against some pathogens and nematodes and it is believed that the effect that Ca has on the cell wall composition helps with resistance to pathogen penetration (Agrios, 2005). Calcium also plays a role in defence against post-harvest pathogens; a reduction of decay is seen with increased calcium concentrations which is likely due to the improved cell wall structure (Conway et al., 1994). Evidence suggest that calcium can improve membrane stability and thus affect potato resistance to heat stress and that physiological disorders are related to Ca deficiencies (Palta, 1996). In a study done by Bester (1993) no correlation between keeping quality and tuber calcium content could be found. Venter suggested that loss of calcium because of its reaction with organic acids might be part of the reason no correlation between keeping quality and tuber calcium content could be found (Venter, 1989). Both macro- and micronutrients occur in potato tubers and influences the physiological status of tubers. Similarly, Mg in potatoes is important for both yield and keeping quality, numerous studies have shown that Mg fertilisation increases the quality of potato tubers (Klein et al., 1982, 1981; Wszelaczynska and Poberezny, 2011). A study showed that increasing Mg levels above the needed amount for maximum yield can increase the keeping quality (Klein et al., 1981). Pectin methylesterase (PME) is an enzyme responsible for removing the methoxyl groups and enabling divalent cations Ca^{2+} and Mg^{2+} to react with pectin and thus creating rigid structures increasing firmness (Tajner-Czopek, 2003). The importance of Mg in crops was intensely reviewed (Gerendás and Führs, 2013) and they concluded that Mg can be considered as the forgotten element in terms of nutrient management in the field, number of studies and intensity of these studies. Although no essential nutrient can be considered more important than another their concentrations and functions differ.

In this study quality was defined as percentage weight loss after 42 days. Stored ware potatoes should not be allowed to wilt and fresh mass loss should not exceed 5% according to Harris (1992). Potato tuber mass consists of 70-80% water and the outer layer skin (phellem) acts as a barrier to prevent water loss through evaporation. The latter accounts for 98% of the water loss in tubers and the remaining 2% is due to direct diffusion through the lenticels (Burton, 1978). Physiological disorders like internal brown spot (IBS) and hollow heart (HH) intensify during storage and it decrease keeping quality of potatoes (Sterrett, 1991).

Wounds that occur because of skinning are difficult to control unless the periderm matured sufficiently, which causes the skin to set and increase skin strength. If the periderm is well developed and intact with its suberin biopolymer it serves as the primary defence against pathogens, insects, water loss and physical piercing into potato tubers (Lulai, 2001). The tuber periderm consists of three layers namely phellem (suberized cells), phellogen (cork cambium) and phelloderm and forms from epidermal tissues (Vreugdenhil et al., 2007). The phellem is the part of the periderm that has been referred to as the skin and skinning is the process where the phellem is removed from the tissue below it (Lulai and Freeman, 2001). Each cultivar has a maximum potential specific gravity (SG) and thus it is a genetic trait, which finds complete ‘expression’ only under long growing seasons with warm day- and cool night temperatures with sufficient water (Smith et al., 1997). The SG is used as a standard in the U.S.A , Holland and RSA for potato quality (Lugt, 1961; Niederwieser and Raan, 2017). For potatoes to qualify for processing it must contain an SG ≥1.075 (“Fact sheet: Internal quality,” 2016). The objective for this study was to develop a measuring tool that can be used to routinely predict the physiological quality of a tuber.

4.3 Materials and Methods

4.3.1 *Description of sampling area*

Sampling was done in the Sandveld and Ceres, more specifically the Kouebokkeveld area throughout 2016 and until June 2017. Both are part of the Western Cape and thus have a Mediterranean climate that is characterised by dry, hot summers with low rainfall. In summer (December-February) growth is regularly inhibited by high temperature while in winter (June-August) photosynthesis limits growth due to low solar radiation intensities (Franke et al., 2011). The Sandveld are close to the South Atlantic Ocean and cool see breezes occur during the day while the Kouebokkeveld are not affected by sea breeze. Strong winds occur in both these areas that can cause damage to plants. The predominant wind in the summer is South-east. Summers have long days and short nights, while short days and long nights occur in winter. The day length and temperature start to decrease in autumn (March-May). In winter cold temperatures and high rainfall occur and in the Kouebokkeveld snowfall and frost are common during winter. The predominant wind in winter is South-western. In the Sandveld the long term annual rainfall is about 300 mm annually (Franke et al., 2011). The rainfall during the main potato growing season is 127 mm for the Sandveld (June) and 107 for the Kouebokkeveld (October) (Van der Waals et al., 2016). During spring (September-November) the day length and temperature begins to increase. The periods described above as winter, spring, summer and autumn were used as the Season treatment in this study.

Both the Sandveld and the Kouebokkeveld contains sandy soils with varying pH, low clay and low C content. Some of these soils are highly saline and high sodium content is also common. Saline soil is classified have an electrical conductivity of a saturated soil extract (EC_e)>4 dS m^{-1}, exchangeable sodium percentage (ESP)<15% and sodic soil EC_e<4 dS m^{-1}, ESP>15% (Richards, 1954). The cation exchange capacity (CEC) of the soils sampled ranged between 1-6 $cmol^{+}.kg^{-1}$ and the ESP values ranged from 1-38%.

The electrical conductivity (EC) of the irrigation water varied from 0.03 dS m^{-1} to 2.18 dS m^{-1}, the irrigation water of the Sandveld having much higher EC as well as higher sodium absorption ratio (SAR) as expected since it is very close to the sea. No yield loss occurs for potatoes with irrigation water of 1.1 $dS.m^{-1}$ but at 1.7 $dS.m^{-1}$ a 10% loss can be expected and at 3.9 $dS.m^{-1}$ a 50% yield loss was reported (Ayers, 1975).

In the Sandveld planting can occur throughout the year, but most are planted in February and June. Planting in the Kouebokkeveld (Op Die Berg) mostly occurs in September to November. Samples taken from the Kouebokkeveld were planted in double rows with sprinkler irrigation while in the Sandveld most were planted in double rows and all under pivot irrigation.

4.4 Data collection

Four to seven plants were sampled to obtain at least 51 undamaged tubers. With each tuber sample a soil and water sample were also taken and it was sent to the Western Cape department of Agriculture's soil, water and plant laboratory at Elsenburg for analyses. Soils were sampled near the tubers on the ridge and between rows by using an auger while water samples were taken at the nearest water source, usually at the pivot. The soil analyses were done with methods adapted from the Non-Affiliated Soil Analysis Work Committee (1990), soil pH was done in KCl and P was determined by the Olsen method (Olsen, 1954). Water analyses for the different elements were done by ICP (Inductively Coupled Plasma Spectrometer) and chlorides and bicarbonates were determined by titration. Tuber analysis was also done by ICP and recorded on a dry weight (DW) basis according to Palic et al., (1998).

Table 4.1. Time of sampling at different trial sites from the production areas as highlighted in the Materials and methods.

Harvest Date	Season	Farm	Region	Latitude	Longitude
28/01/2016	Summer	Sandberg	Sandveld	32°17'17.85"S	18°31'22.34"E

28/01/2016	Summer	Sandberg	Sandveld	32°17'22.23"S	18°31'11.36"E
24/02/2016	Summer	Vredelust (Op die berg)	Ceres	32°50'33.13"S	19°14'24.56"E
24/02/2016	Summer	Vredelust (Op die berg)	Ceres	32°50'56.10"S	19°14'24.91"E
23/03/2016	Autumn	Vredelust (Op die berg)	Ceres	32°49'43.28"S	19°14'59.09"E
23/03/2016	Autumn	Vredelust (Op die berg)	Ceres	32°49'42.26"S	19°15'9.02"E
23/03/2016	Autumn	Vredelust (Op die berg)	Ceres	32°50'3.35"S	19°15'54.77"E
23/03/2016	Autumn	Vredelust (Op die berg)	Ceres	32°49'55.92"S	19°15'38.27"E
7/3/2016	Autumn	Rietfontein	Sandveld	32°38'15.93"S	18°28'54.15"E
7/3/2016	Autumn	Rietfontein	Sandveld	32°38'13.39"S	18°29'5.56"E
7/3/2016	Autumn	Saamstaan	Sandveld	32°34'6.27"S	18°21'45.86"E
7/3/2016	Autumn	Saamstaan	Sandveld	32°34'5.29"S	18°21'54.99"E
11/5/2016	Autumn	Saamstaan	Sandveld	32°35'38.14"S	18°20'38.59"E
11/5/2016	Autumn	Saamstaan	Sandveld	32°35'42.30"S	18°20'22.70"E
1/4/2016	Autumn	Sebulon	Sandveld	32°21'18.78"S	18°27'47.46"E
1/4/2016	Autumn	Sebulon	Sandveld	32°21'24.01"S	18°27'41.62"E
19/04/2016	Autumn	Strandfontein	Sandveld	31°46'44.39"S	18°14'37.62"E
19/04/2016	Autumn	Strandfontein	Sandveld	31°46'46.29"S	18°14'45.09"E
11/5/2016	Autumn	Vredelust	Sandveld	32°31'33.24"S	18°30'21.76"E
11/5/2016	Autumn	Vredelust	Sandveld	32°31'27.88"S	18°30'12.49"E
6/7/2016	Winter	Bakserug	Sandveld	32° 8'26.54"S	18°51'36.82"E
6/7/2016	Winter	Bakserug	Sandveld	32° 8'20.44"S	18°51'33.11"E
20/10/2016	Spring	Saamstaan	Sandveld	32°38'48.50"S	18°23'59.10"E
20/10/2016	Spring	Saamstaan	Sandveld	32°38'58.40"S	18°24'0.20"E
1//11/2016	Spring	Knapdaar	Sandveld	32°50'36.10"S	18°32'56.10"E
1/11/2016	Spring	Knapdaar	Sandveld	32°50'36.60"S	18°32'42.90"E
1/11/2016	Spring	Bodam	Sandveld	32°14'7.20"S	18°29'1.00"E
1/11/2016	Spring	Bodam	Sandveld	32°13'58.70"S	18°29'0.20"E
14/11/2016	Spring	Sandberg	Sandveld	32°19'1.00"S	18°31'18.30"E
14/11/2016	Spring	Sandberg	Sandveld	32°19'5.80"S	18°31'5.20"E
14/11/2016	Spring	Bodam	Sandveld	32° 9'55.70"S	18°32'40.30"E
14/11/2016	Spring	Bodam	Sandveld	32°10'3.43"S	18°32'41.42"E
14/11/2016	Spring	Bakserug	Sandveld	32° 9'13.60"S	18°52'2.70"E
14/11/2016	Spring	Bakserug	Sandveld	32° 9'7.90"S	18°52'13.70"E
5/12/2016	Summer	Bodam	Sandveld	32°12'27.40"S	18°34'42.30"E
5/12/2016	Summer	Bodam	Sandveld	32°12'30.40"S	18°34'48.20"E
5/12/2016	Summer	Bodam	Sandveld	32°12'30.04"S	18°34'18.56"E

5/12/2016	Summer	Bodam	Sandveld	32°12'36.10"S	18°34'17.20"E
5/12/2016	Summer	Spioenkop	Sandveld	32°11'52.00"S	18°30'15.10"E
5/12/2016	Summer	Spioenkop	Sandveld	32°11'51.30"S	18°30'4.50"E
28/02/2017	Summer	Saamstaan	Sandveld	32°33'50.40"S	18°20'49.60"E
28/02/2017	Summer	Saamstaan	Sandveld	32°33'38.30"S	18°22'38.40"E
28/02/2017	Summer	Saamstaan	Sandveld	32°34'29.60"S	18°22'35.40"E
28/02/2017	Summer	Spioenkop	Sandveld	32°11'46.80"S	18°23'50.70"E
28/02/2017	Summer	Spioenkop	Sandveld	32°11'55.30"S	18°23'54.20"E
28/02/2017	Summer	Bodam	Sandveld	32°13'9.30"S	18°30'25.50"E
28/02/2017	Summer	Bodam	Sandveld	32°13'14.40"S	18°30'20.50"E
13/03/2017	Autumn	Rietfontein	Sandveld	32°38'3.49"S	18°28'21.43"E
13/03/2017	Autumn	Rietfontein	Sandveld	32°38'6.70"S	18°28'26.70"E
15/03/2017	Autumn	Vredelust (Op die berg)	Ceres	32°50'11.20"S	19°15'52.59"E
15/03/2017	Autumn	Vredelust (Op die berg)	Ceres	32°50'14.36"S	19°15'40.08"E
15/03/2017	Autumn	Vredelust (Op die berg)	Ceres	32°50'55.51"S	19°14'47.99"E
15/03/2017	Autumn	Vredelust (Op die berg)	Ceres	32°49'17.63"S	19°15'23.24"E
3/4/2017	Autumn	Bodam	Sandveld	32°12'2.90"S	18°32'27.70"E
3/4/2017	Autumn	Bodam	Sandveld	32°11'54.50"S	18°32'16.30"E
3/4/2017	Autumn	Saamstaan	Sandveld	32°34'45.80"S	18°20'34.50"E
3/4/2017	Autumn	Saamstaan	Sandveld	32°34'46.50"S	18°20'14.80"E
5/5/2017	Autumn	Bodam	Sandveld	32°10'3.38"S	18°32'16.88"E
5/5/2017	Autumn	Bodam	Sandveld	32°10'10.42"S	18°32'10.38"E
14/6/2017	Winter	Bakserug	Sandveld	32° 8'42.75"S	18°51'49.98"E
14/6/2017	Winter	Bakserug	Sandveld	32° 8'36.64"S	18°51'55.82"E

The day after sampling tubers were washed with a diluted Sporekill (didecyldimethyl ammonium chloride) concentration of 0.02% (v/v). All soil debris and excess materials were removed. Sorting occurred by removing any damaged, green or disease infected tubers from the sample set. Any tubers <26 mm in diameter were removed from the sample set. Tubers were then classified as large, medium or small based on the sample set. Tubers were then left to dry on white paper towels.

The following process was repeated for large, medium and small tubers and for storage at 25°C and 5°C. Three tubers were weighed and skin-set was tested by using the farmers' method by rubbing the skin with the thumb (Kabira and Lemaga, 2003). Each tuber was given a score out of five for each time the skin was removed by a rub, they were then sent to Elsenburg for analyses of Ca, B, Na, K, P and Mg content. Three tubers were weighed on day one, and physiological disorders HH and IBS were recorded by cutting the tubers into pieces of eight and giving it a rating out of 8. Thus, the distribution and not the intensity was measured.

The SG of three tubers per sample was measured on day one. The water displacement method was used (Tabatabaeefar, 2002). Tubers were submerged into a known water volume and the volume water displaced is measured. Specific gravity was than determined by dividing tuber mass in grams by the displaced water volume (mm). Tubers stored as ware potatoes were stored at 25°C and weighed at day 1, 7, 14, 28 and 42. Storage at 25°C was done in a dark ventilated room, but without controlled air humidity or temperature control. Tubers stored as seed potatoes were stored at 5°C and weighed at day 1, 28 and 42. Storage at 5°C was done in a ventilated dark room, but without controlled air humidity or light. Percentage mass loss was determined after storage on day 42. Firmness was determined at the end of the storage period by hand and giving it an index value from one to five, for statistical purposes three was left out, while one and two were classified as soft and four and five as firm. Sprouts were classified when growth were > 4mm although 2-3 mm has been used in the past for criteria for the end of dormancy (Van Ittersum, 1992). The purpose of this length of sprouting is to ensute that continual growth has occurred.

4.5 Statistical analyses

No treatments were applied in this study and variation occurred due to different cultivation methods, areas and planting dates, the results are therefore presented by running different statistical models including multiple correlation analysis. Both PCA (Principal Component Analysis) and PLS (Partial Least Squares) were done by using the statistical programme XLSTAT. Partial least squares can be used to predict various dependent variables from different independent variables. Both the independent and dependent variables for PLS component one and two enables one to firstly, conclude on the relationship between variables of the data set and secondly on the relationship between independent and dependent variables (Payne et al., 2007). A procedure for cross-validation is used for ensuring that the correct number of dimensions is included in both PCA and PLS (Helland, 1988). The tuber quality characteristics (x variables) with a VIP score larger than 1 are considered important in making the prediction following (Chong and Jun, 2005). Studies in agriculture and on potatoes have been conducted using PCA and PLS statistical methods (Smith et al., 2009).

4.6 Results and Discussion

Using PCA for cross-validation for the physiological quality models created with PLS one can see that % mass loss positively correlated with % softness at both 5°C and 25°C as expected. Calcium and Ca:Mg ratio correlated better with % softness and % mass loss at 5°C and 25°C while Mg correlated better with % frimness at 5°C both and 25°C (see Figure 4.1). This was true for PCAs done for large, medium and small tubers. A single estimation procedure to relate both *x* and *y* matrices are used for PLS whereas in PCA each component is a linear combination of only the *x* variables (Helland, 1988).

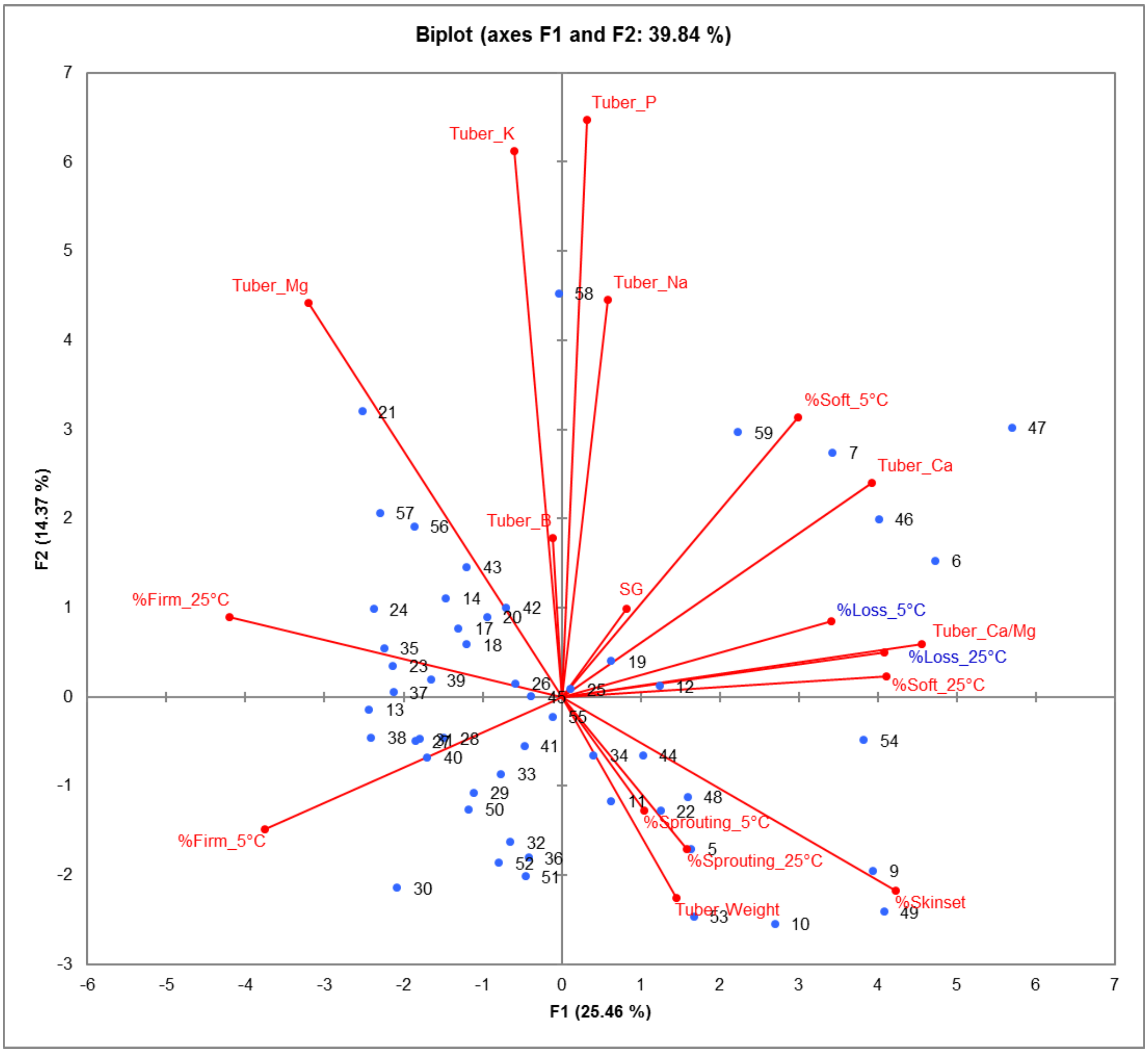

Figure 4.1. Principle component analysis for the associations of the tuber characteristics predicting the percentage mass loss in large tubers stored at 5°C and 25°C respectively after 42 days.

4.5.1 Mass loss (first) prediction

For the large, medium and small PLS percentage weight loss was the first prediction done at both 5℃ and room temperature (25°C) storage. The set of dependent variables including mass loss, softness, firmness and sprouting was in the second prediction. Independent variables used for making the predictions were skinning, Ca:Mg, Mg, Ca, SG, B, K, P, Na and the tuber mass used in nutrient analyses. The independent variables with VIP1 values >1 were used for weight loss prediction and VIP2 >1 were used for the set off dependent variables (see Table 4.2). For large tubers stored both at 25°C and 5°C mass loss prediction had the highest R^2 values indicating these predictions were the most accurate (see Table 4.3).

Table 4.2. Large, medium and small values for VIP 1 and VIP 2. VIP 1 was used to predict dependent variable, i.e. % mass loss and VIP 2 was used to predict the set of dependent variables, namely % mass loss, % softness, % firmness and % sprouting.

Variable	Large 5 °C		Medium 5 °C		Small 5 °C	
	VIP 1	VIP 2	VIP 1	VIP 2	VIP 1	VIP 2
%Skinning	1.734	1.402	0.598	0.811	1.090	1.585
Tuber Ca:Mg	1.427	1.342	1.903	1.634	1.927	1.626
Tuber Mg	0.683	0.874	1.131	1.070	1.021	0.821
Tuber Ca	1.342	1.187	1.641	1.406	1.675	1.434
SG	0.328	0.909	1.087	0.940	0.489	0.768
Tuber B	0.878	0.901	0.701	0.600	0.058	0.060
Tuber K	0.503	0.505	0.201	0.188	0.152	0.120
Tuber Mass	0.962	1.024	0.010	0.885	0.955	0.772
Tuber P	0.790	0.853	0.218	0.319	0.067	0.206
Tuber Na	0.084	0.623	0.538	1.178	0.263	0.932
	Large 25 °C		Medium 25 °C		Small 25 °C	
	VIP 1	VIP 2	VIP 1	VIP 2	VIP 1	VIP 2
%Skinning	1.755	1.617	0.683	1.144	0.792	0.838
Tuber Ca:Mg	1.695	1.500	1.918	1.557	1.896	1.725
Tuber Mg	1.447	1.276	1.445	1.178	1.523	1.386
Tuber Ca	1.305	1.168	1.662	1.350	1.565	1.425
SG	0.041	1.064	0.327	0.920	0.299	0.468
Tuber B	0.040	0.627	0.706	0.712	0.706	0.800
Tuber K	0.205	0.557	0.098	0.082	0.327	0.309
Tuber Mass	0.430	0.397	0.094	0.827	0.274	0.443
Tuber P	0.006	0.362	0.239	0.198	0.467	0.426
Tuber Na	0.142	0.147	0.572	0.987	0.145	1.019

At 5°C and 25°C storage PLS prediction models for the large, medium and small tubers Ca and Ca:Mg ratio were relevant each time and it correlated positively with % weight loss (Figures 4.2 and 4.3). It is important to note that there is a bias when overall Ca is compared in large tubers since the periderm contains much more Ca than the flesh (Bamberg et al., 1993). Thus, Ca had the same effect in the large, medium and small tubers. Calcium and Mg are strongly competitive and it seems that the plasma membrane binding site at the root has higher affinity for Ca^{2+} than for the highly hydrated Mg^{2+} (Marschner, 1995).

Magnesium was only irrelevant in large tubers at 5°C storage. For the rest of the tubers Mg was relevant and it correlated negatively with mass loss, meaning tubers with higher keeping quality also had higher Mg content (Figures 4.2 and 4.3). Seemingly, Mg concentrations in these potatoes were insufficient for optimum keeping quality except for the large tubers stored at 5°C. Potatoes are considered to be relatively sensitive to Mg deficiencies and specific cation uptake at the expense of another as previously mentioned is a known phenomenon (Bear et al., 1951; Hochmuth, 2007; Marschner, 2012). Early senescence due to low N concentrations, drought, water logging or compaction causes Mg deficiencies and foliar sprays will most likely not alleviate these types of deficiencies. Determinate cultivars are seemingly more susceptible to these types of deficiencies (Allison et al., 2001). Considerable fewer studies have been done on Mg and it has been stated that it is the “orphan nutrient” compared with Ca (Rosanoff, 2010).

Skinning was relevant in the 25°C storage for the large tubers, whereas at 5°C storage skinning was relevant for both small and large tubers. The latter correlated positively as expected because potatoes with lower skin strength usually have an immature periderm and more mass loss will occur. Specific gravity was only significant in medium tubers at 5 °C storage and correlated positively, higher SG tubers tend to have lower mechanical damage (Kaya et al., 2000) and a decrease in bacterial soft rot caused by *Erwinia carotovora* subsp. atroseptica (Wright et al., 2005). In this study, tubers were hand harvested and no mechanical damage occurred. Tubers with HH will have significantly lower SG than healthy tubers (Kleinkopf et al., 1987) and since low incidences of HH and IBS were found in this study, which might explain why SG showed little importance in making the prediction.

Phosphorus, K, Na, B and tuber mass were not significant in any of the models in making the weight loss prediction. The reason may be because both Ca and Mg had a pronounced effect on keeping quality in this study. Internal brown spot and HH occurred in very few of the tubers tested and it was decided not to include these parameters in the quality prediction models.

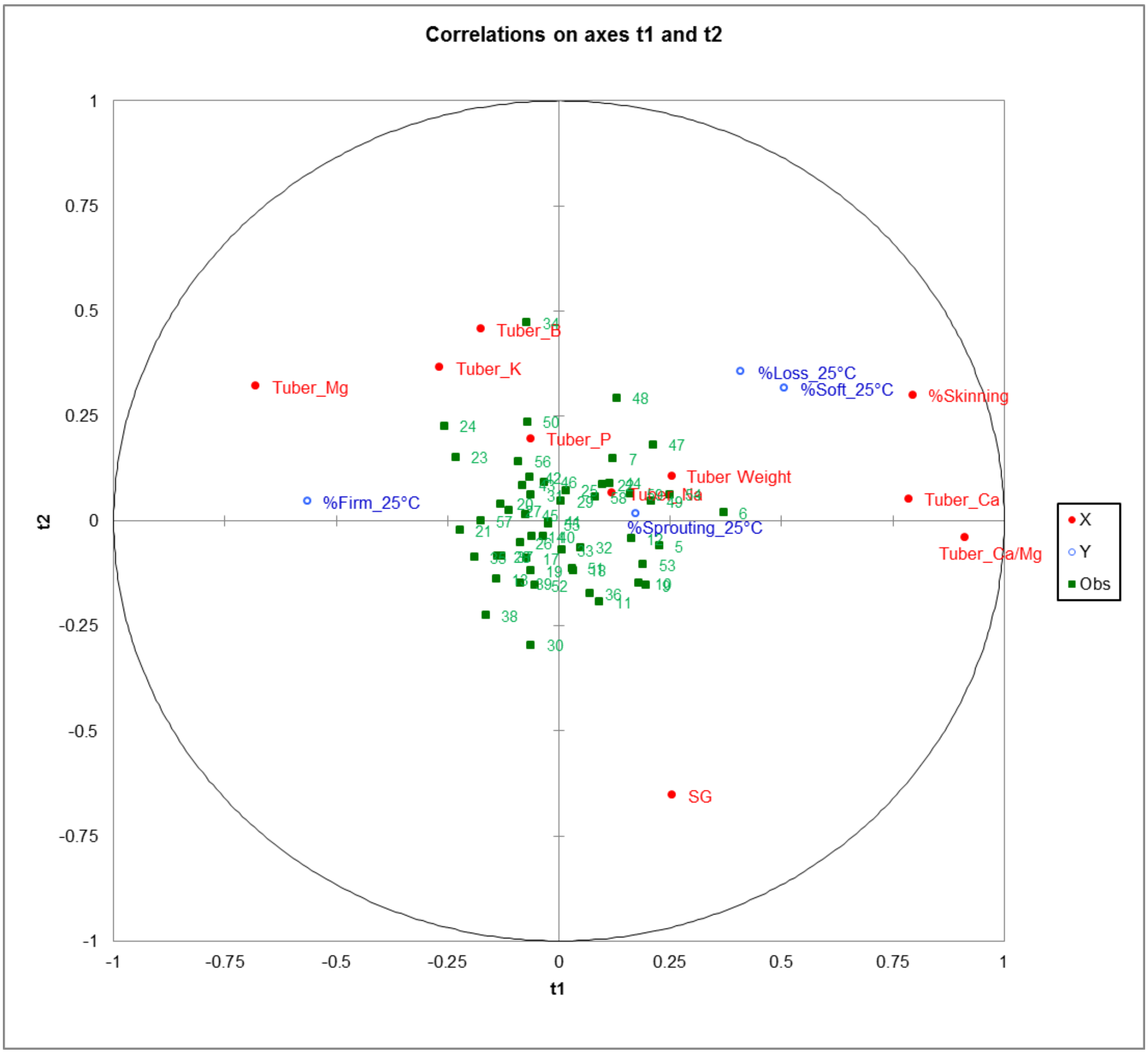

Figure 4.2. Partial least squares model prediction for the percentage mass loss after forty-two days of storage at 25℃ for the large tubers using tuber characteristics.

4.6.2 Independent set of variables (second) prediction

The set off dependent variables included mass loss, softness, firmness and sprouting. Of these, sprouting was very difficult to predict because few tubers had sprouted and many external factors such as environmental conditions during growth and storage conditions are known to affect potato sprouting ability. Softness and firmness prediction had the same tendency with Ca, Ca:Mg ratio and Mg since softness positively correlated with mass loss and firmness negatively. Tubers with higher Ca and Ca:Mg ratios tended to be softer and tubers with higher Mg correlated better with firmness (Figures 4.1, 4.2 and 4.3). Magnesium sulphate fertilisation has previously shown to increase firmness in terms of a decrease in deformation of tubers after a 5 month storage period at 5 °C (Klein et al., 1982).

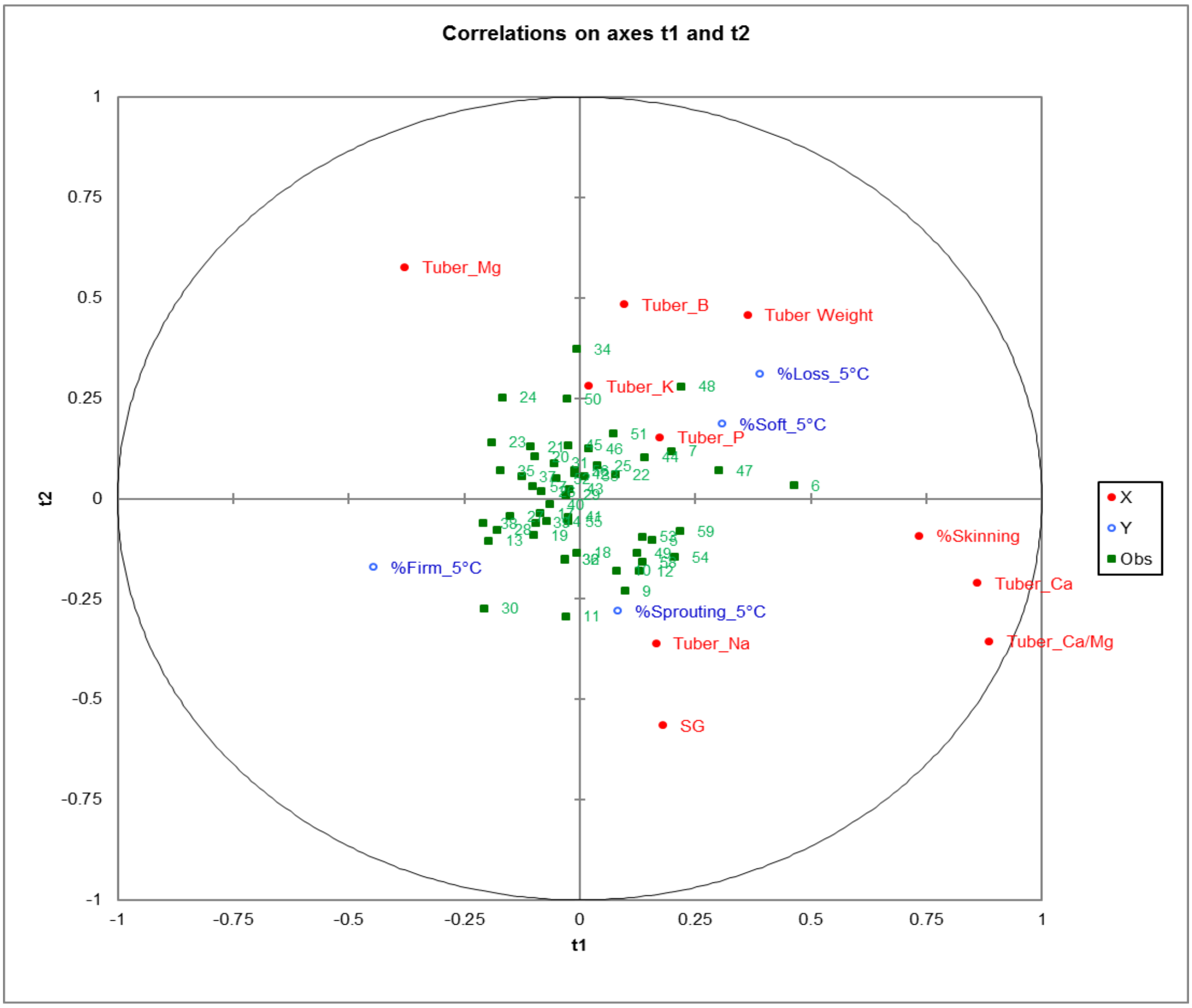

Figure 4.3. Partial least squares (PLS) model prediction for the percentage weight loss after forty-two days of the storage at 5°C for the large tubers using tuber characteristics.

Table 4.3. R^2 values for predictions made for large-, medium- and small tubers at storage temperatures of 5°C and 25°C, respectively.

	R squared values					
Dependent variable	**Large 5**	**Large 25**	**Medium 5**	**Medium 25**	**Small 5**	**Small 25**
% Mass loss	0.499	0.561	0.355	0.461	0.461	0.449
% Softness	0.380	0.622	0.620	0.303	0.309	0.384
% Firmness	0.470	0.562	0.588	0.418	0.642	0.446
% Sprouting	0.266	0.379	0.530	0.570	0.612	0.354

4.7 Conclusion

Specific gravity has long been used to give an estimation of the DM accumulation and starch content (SC) of potato tubers in a non-destructive way (Burton, 1989). Thus, SG, DM and SC are highly important quality characteristics, whose importance are justified because it determines a tuber's suitability for processing as well as propensity for mechanical damage or bruising (Kaya et al., 2000). Specific gravity was only significant in one model for predicting % mass loss for Sifra. Better keeping quality was expected with higher SG but because HH, mechanical damage and tuber decay were at a minimum it could have affected the results. A firm intact matured periderm is very important for preventing mass loss and improving keeping quality of potatoes (Lulai and Freeman, 2001). Higher % skinning tubers showed higher mass loss and negatively affected the keeping quality.

This study only investigated at the keeping quality and although lower Ca concentration showed increased keeping quality in tubers lower Ca fertilisation will most likely lead to a yield reduction and increase of IBS and hollow heart. Disorders in potato tubers have been linked to Ca deficiencies and its importance in increasing potato yield and quality is well known (Combrink and Hammes, 1972). Calcium is immobile and moves through the transpiration stream. Poor skin quality might increase transpiration in tubers explaining increased Ca concentrations in tubers with poor quality skin (Ginzberg et al., 2012). The same affect might have been the reason for decreased keeping quality in tubers with higher Ca concentrations.

Calcium has been studied extensively in terms of role in plants, uptake and improving the quality of potatoes. In contrast, Mg has been neglected and its role might have been underestimated in increasing the keeping quality of potatoes. This study showed that higher Mg containing potatoes had lower mass loss and better keeping quality and that decreasing the Ca:Mg ratio in tubers might improve storability. The bulk of Mg uptake in potato tubers occurs during tuber initiation which possibly presents the best stage of intervention to increase the response to supplemental Mg (Zhao et al., 2010). Even though Mg is highly mobile (Marschner, 1995), during canopy senescence redistribution from the leaves and haulm to the tubers will take place but deficiencies may still prevail.

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CHAPTER 5

General discussion and conclusions

5.1 Overview

This study was conducted to create a model for predicting mass loss through identifying certain tuber characteristics and using them in the model. The rate (g d^{-1}) of mass loss varied between tubers of different sizes, mass loss in descending order, large <medium <small. For this study the rate was constant through 42 days at both 5°C and 25°C storage. Percentage mass loss differed as well, in descending order, small < medium <large. Heltoft et al., (2017) concluded that a cultivar specific weight loss model should be considered, and this study focussed on the Sifra cultivar. Soil and water characteristics failed to give consistent results to help predict the keeping quality of potatoes and so the focus remained on the tuber characteristics to predict the keeping quality of potatoes.

Specific gravity (SG) is of importance because it determines tubers suitability for processing as well as mechanical damage or bruising (Kaya et al., 2000). In this study SG was markedly higher in medium tubers, which concur with literature (Ifenkwe et al., 1974). It was only significant in one model for predicting % mass loss and correlated positively with mass loss, which was not expected. Better keeping quality was expected with higher SG but because HH, mechanical damage and tuber decay was at a minimum it could have affected the results.

A firm, intact mature periderm is very important for preventing mass loss and improving keeping quality of potatoes (Lulai and Freeman, 2001). Higher % skinning tubers showed higher mass loss that negatively affected the keeping quality. Skinning was relevant in some instances in predicting mass loss, but was inconsistent. It correlated positively as expected because potatoes with lower skin strength usually have an immature periderm and more mass loss will therefore occur. For predicting weight loss, skin set and thus tuber resistance to skinning was found to be very important (Heltoft et al., 2017). Findings from this study concur with these findings. Cut tubers were also studied to see if it can be used to predict mass loss of stored potatoes. However, no correlation could be found in this study.

The role of Ca in quality of fruit and vegetable, especially potatoes have been studied extensively in literature, thus it was expected to correlate positively with keeping quality. Findings from this study strongly refute this notion. Although Ca correlated positively with mass loss for all the different tuber sizes, it seems Mg correlated negatively with mass loss. As previously stated, the possibility exists to get a better correlation with problems such as internal brown spot (IBS) and poor keeping quality if Ca-pectate rather than total Ca can be measured (Seling et al., 2000).

Calcium concentration was highest in the small tubers followed by medium and lastly large tubers. Significantly higher Ca contents occurred in autumn than in spring and the large tubers with the lowest Ca concentration had the highest incidence of IBS, since Ca-deficiencies are the cause of IBS this result was expected. Disorders in potato tubers have been linked to Ca deficiencies and its importance in increasing potato yield and quality is well known (Combrink and Hammes, 1972). Poor skin quality might increase transpiration in tubers explaining increased Ca concentrations in tubers with poor quality skin (Ginzberg et al., 2012). The same effect might have been the reason for decreased keeping quality in tubers with higher Ca concentrations since higher transpiring tubers will have higher percentage mass loss.

Increasing Ca through genetic transformation has been done (Park et al., 2005), yet care must be taken not to neglect Mg and over emphasise Ca importance. Magnesium has a very important role in the quality of tubers and Ca can compete with tubers for uptake and binding position (Lazarević et al., 2011). If tubers are genetically transformed to acquire higher Ca levels at the expense of Mg, deficiencies of the latter may occur.

Calcium has been studied extensively in terms of role in plants, uptake and improving the quality of potatoes. This has sometimes been to the detriment of other minerals such as Mg whose role might have been underestimated in increasing the keeping quality of potatoes (Gerendás and Führs, 2013; Rosanoff, 2010). Magnesium concentrations did not differ in tuber sizes and Ca: Mg ratio followed the total Ca trend in terms of size and seasonal differences and may therefore have been driven by total Ca. This study showed that higher Mg containing potatoes had lower mass loss and better keeping quality and that decreasing the Ca:Mg ratio in tubers might improve storability. The bulk of Mg uptake in potato tubers occurs during tuber initiation (Zhao et al., 2010), and it is thus this is the the best phase to increase Mg fertilisation. Even though Mg is highly mobile and during canopy senescence redistribution from the leaves and haulm to the tubers will take place, deficiencies can and does still occur (Marschner, 1995).

Limitations occurred in this study, one such limitation could be that total Ca was measured and not Ca pectate or any other Ca fraction. This was initially planned but it was unsuccessful, a realistic protocol could not be established in time. Furthermore, future research might benefit from pot trials, specifically to establish the relationship among Ca pectate with IBS and keeping quality since field trials without treatments can be limiting. This study also serves as an indication that research for potato quality should refocus itself from specific nutrients and rather try to find the balance between nutrients for specific cultivars.

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