IMPROVEMENT OF YIELD AND QUALITY ON PROCESSING POTATO (*SOLANUM TUBEROSUM* L.) BY UNDERSTANDING THE INTERACTIVE EFFECTS OF SOIL CHARACTERISTICS AND PLANT NUTRIENT MANAGEMENT IN HOKKAIDO, JAPAN

2019

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北海道の加工用バレイショ生産における
土壌特性と作物養分管理の相互的な影響の
解明による収量と品質の向上

平成 31 年

（2019）

岩手大学大学院連合農学研究科

博士課程　生物生産科学専攻

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CHAPTER 1. GENERAL INTRODUCTION

1.1. Potato and global food security

World human population is expected to increase from 7 billion to 9.5 billion and the demand for food to increase by 70% by 2050 (Bruinsma 2009; Alexandratos and Bruinsma 2012). Half of the current world human population have nutritional problem, with about 2 billion people hungry or malnourished (Sharma et al. 2016). To make matters worse, the ongoing population growth makes it more difficult to expand the cropping area due to urbanization and pressure from alternative uses of land. Increase in crop productivity is required to keep pace with the ongoing population growth and food demand. Potato (*Solanum tuberosum* L.) production can make an important contribution to help ease the current and future turmoil in world food supply and demand.

Potato is the world`s number one non-grain food commodity with a high nutritional content. It is an excellent source of carbohydrates, vitamins, and minerals important for food security and human health (White et al. 2009). The United Nations declared the year 2008 as `The year of potato` to raise awareness of the potato in addressing nutritional issues of global concern (UN 2006). Carbohydrate constitutes about 75% of total potato dry matter mainly in form of starch that is a good source of dietary energy (Storey 2007; Birch et al. 2012). Potato also have high levels of vitamin C, and studies have shown that an average of 175 g potato can provide over 40% of Recommended Daily allowance for vitamin C (Storey 2007). In addition, the crop is also a major source of anthocyanin and carotenoid pigments that are potent antioxidants known to have beneficial effects in human health (Brown 2005; Taylor and Ramsay 2005). Owing to nutritional benefits described above, FAO recommended potato as a strategic food security crop as the world faces not only uncertainties in food supply but also steady hunger rates (FAO 2009).

Although potato is considered as a minor world food crop in tonnage behind wheat, rice and corn, it has a high per area use efficiency and energy production potential than cereal crops. It produces more dry matter and protein per hectare than major cereal crops (Burton 1989) and have water utilization efficiency of up to seven times greater than cereal crops (International Potato

Center 2018). In terms of harvest index, up 85% of the potato plant is edible human food, compared with around 50% for cereals (Kooman and Haverkort 1994; Hay 1995). In developing countries, potato plays a big role in poverty alleviation and serves as a hunger breaking crop, as it has a relatively short cycle in some cropping systems (Gildermacher et al. 2009; Haverkort and Struik 2015). The crop is also used as a cash crop and that not only does it contribute to poverty reduction by increasing income but also creates employment (Thiele et al. 2010).

Potato crop is an important agricultural product grown worldwide in terms of planted areas (FAO 2016). The crop has been adapted for cultivation in a wide range of environments that differ significantly with regard to latitude, altitude, day length, temperature and soil fertility (Hijmans 2001; De Jong 2016). Currently, it is grown in more than 150 countries (FAO 2016) from latitudes of 65^{o}N to 50^{o}S and from altitudes ranging from sea level to 4000 m, demonstrating the adaptability of this crop to many environmental conditions. The ability to adapt to potato to withstand multiple biotic and abiotic stresses is important to its future growth as a major food source (Birch et al. 2012).

The crop can be consumed fresh, used for starch production or processed into products such as chips and French fries. While the demand for food in developing countries is changing away from cereal-based diets towards potatoes (Scott and Suarez 2011; De Jong 2016), consumer demand for potatoes in developed countries including Japan is changing from fresh potatoes to value added processed food products such as chips (Wang et al. 2012). Given the potato`s high productivity per unit area of land and its value as both a staple and a cash crop, increasing stress tolerance in potato has great potential to contribute to food and income security.

1.2. Potato production in Japan

In Japan potato is also important crop with consumer demand exceeding domestic supply (MAFF 2015), with limited availability of imported fresh potato tubers due to difficulties to quarantine (Nagatomo 2012). Potatoes are grown throughout the year, as a winter crop free from frost in Okinawa and summer crop free from heat in Hokkaido (Deguchi et al. 2016). In terms of cost of production, Japan has a competitive advantage over most potato producing countries in the world as it does not require irrigation as it receives abundant precipitation throughout the growing season (Deguchi et al. 2016). Although Japan can produce 2.2 million tons of potato annually on 79,700 ha of land, the total annual demand is estimated at 3.5 million tons (GAIN 2014).

Hokkaido, the northernmost region of Japan is the major producer of potatoes that account for 80% of the nation's production (MAFF 2016). The region is characterized by its cool temperatures and large-scale agricultural land that provide suitable conditions for potato production. Thirty-five percent of the arable land in Hokkaido is covered by soils of volcanic origin, classified as Andisols. Generally, these soils have high water holding capacity and excellent physical properties for root growth that contribute to high yields of upland crops (Saigusa et al.1987). However, in uncultivated fields, soil available phosphate is very low and thus it is one of the most limited plant nutrients for growth and development (Shoji et al. 1993). Low phosphate availability to plants results not only from natural phosphate deficient in the soils but also their high capacity to fix large amounts of phosphate in a ligand exchange reactions with Al-OH and Al-H_2O functional groups. Potato crop in these soils therefore, requires high amounts of phosphate fertilizer to reach economically acceptable yields due to shallow root system (Alvazerez-Sanchez et al. 1999; Iwama 2008). Despite these limitations, climatic conditions that prevail in Hokkaido region are considered to be suitable and have potential for high yields when crop is managed properly.

Potato yields have been increasing significantly worldwide since the start of green revolution 50 years ago (Fig. 1.1a), partly as a result of increased use of fertilizers, fungicides, and irrigation (White et al. 2009). And also, the worldwide increase in potato production has resulted from increase in production areas particularly in developing countries (FAO 2015). In contrast, the domestic supply of potatoes in Japan has not changed since 1990s (Fig. 1.1a), and has not been meeting the required demand (FAO 2016). In addition, there is a decreasing trend in potato cultivated area from 235,000 ha in 1949 to 79, 626 ha in 2016 (Deguchi et al. 2016). As a result the country is not self-sufficient in potato and substantial proportion of potato products consumed in the country are imported from USA to meet the demand (Nagatomo 2012; Deguchi et al. 2016).

According to the Ministry of Agriculture, Forestry and Fisheries, 33% of potatoes in Japan are for table use, the starch industry uses 36% while processing sector uses 24% of potatoes. The remaining 7% is used as seed potatoes and feed. The majority of processed potato products are chips (67%) followed by frozen products (18%) and potato salad (9%; GAIN 2014). While consumption of processed food products was negligible in Japan in 1970s (Mori et al. 2015), about 24% of the nation's annual potato production is used in processing industry (GAIN 2014). Moreover, a recent study has shown a gradual shift in potato production from starch to processing cultivars (Deguchi et al. 2016) that underlies the need to increase production of processing potatoes in Japan.

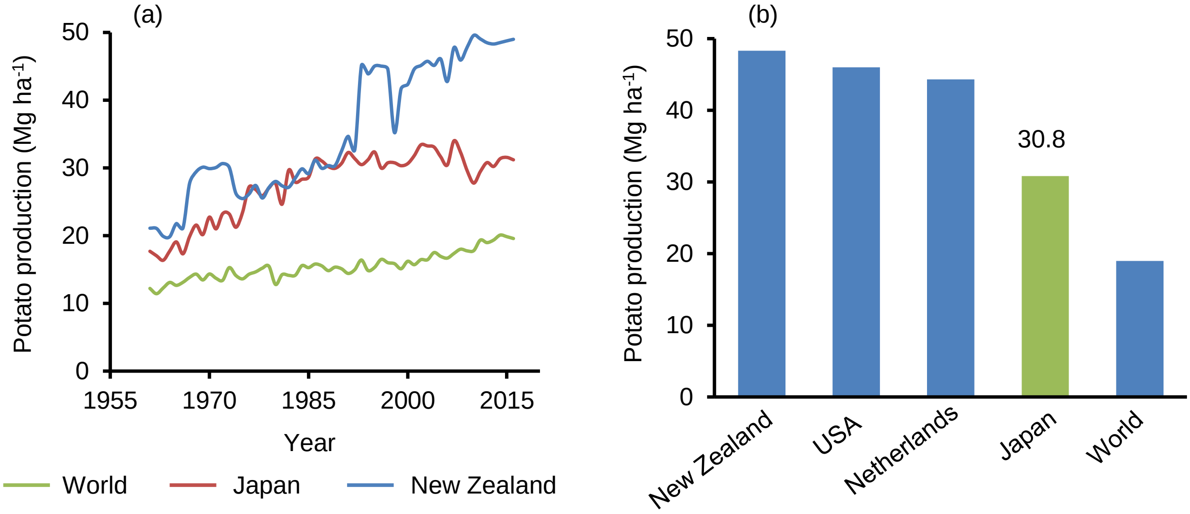


Figure 1.1. (a) The trend of potato production in Hokkaido, Japan, and the world from 1961 to 2016, and (b) average potato yield for 10 years (2007 to 2016) for New Zealand, USA, Netherlands, Japan and the world. Source: FAOSTAT (2016).

1.3. Potato yield potential

In ideal condition, the maximum yield or potential yield is determined by environmental factors such as carbon dioxide, solar radiation, temperature and cultivar characteristics (Fig. 1.2). These environmental factors regulate biological processes such as transpiration, photosynthesis, and respiration in a plant while cultivar is a primary factor determining yield potential. In the field condition, yield is limited by abiotic factors such as soil nutrients and water. Yield is further reduced by weeds, pest and diseases, and the difference between the actual yield realized by growers and potential yield is called yield gap (van Ittersum et al. 2013). Despite the investments and expertise that goes into potato production, the productivity of potato is quite low in Japan compared to major world potato producing countries like USA and New Zealand (FAO 2016). Past studies have shown that the magnitude of yield production increase on croplands depends on the difference between the actual yields and potential yields in a given agro-ecological system (Svubure et al. 2015). Although it is difficult reduce yields to zero, empirical analyses suggested minimum limits to gaps of 20 to 25% of potential yields (van Ittersum et al. 2013). The actual yield of potato in Japan is 30.8 Mg ha^{-1} (Fig. 1.1b; FAO 2016) against the potential yield of 77 Mg ha^{-1} (Deguchi et al. 2016), revealing that there is a huge potential to increase potato production. Yield gap has been used to explore major limiting factors in production, and also as an indicator for the possibility of increasing crop yields in a given region (van Ittersum and Rabbinge 1997).

Although studies exploring the causes of yield gap in Japan have not been widely done, there are quite a few reports documenting factors that limit potato yield in Japan. According to Mori et al. (2015) pest and diseases such cyst nematodes are among the major factors reducing potato yields in Japan. Unfortunately, cyst nematode resistant cultivars such as Early starch and Astarte have low yields. Recent reports indicate that replacement of low dry matter starch cultivars such as Benimaru with high dry matter cultivars such as Konafubuki have led to increase in starch yields but decrease in fresh yields (Deguchi et al. 2016). In the same study, it was reported that the ongoing change in consumer demand for potato processing products has led to introduction of more processing cultivars that are associated with low yields compared to cultivars bred for starch yields. Using crop growth simulation model LINTUL-POTATO-DSS, Deguchi et al. (2016) compared actual and potential yields levels of potatoes grown in summer, spring, Autum, and Winter in different production areas of Japan. The results showed that yield gap varied considerably among various production sites. The crop growth model accounted for climate, planting and harvesting dates and it was concluded that potential yields were limited by the length of growing season and solar radiation.

One of the options to increase food production is by narrowing the yield gap and nutrient management has been shown to be the major cause of potato yield gaps in Yin-mountain hilly area of China (Jia et al. 2018). Other studies have demonstrated the relationships between nutrient use and water management in different crops to improve yield and nutrient use efficiency (Li et al. 2011). Maintaining adequate levels of soil fertility has been shown as one of the management practices that affect growth, development and crop yields (Tisdale et al. 1995).

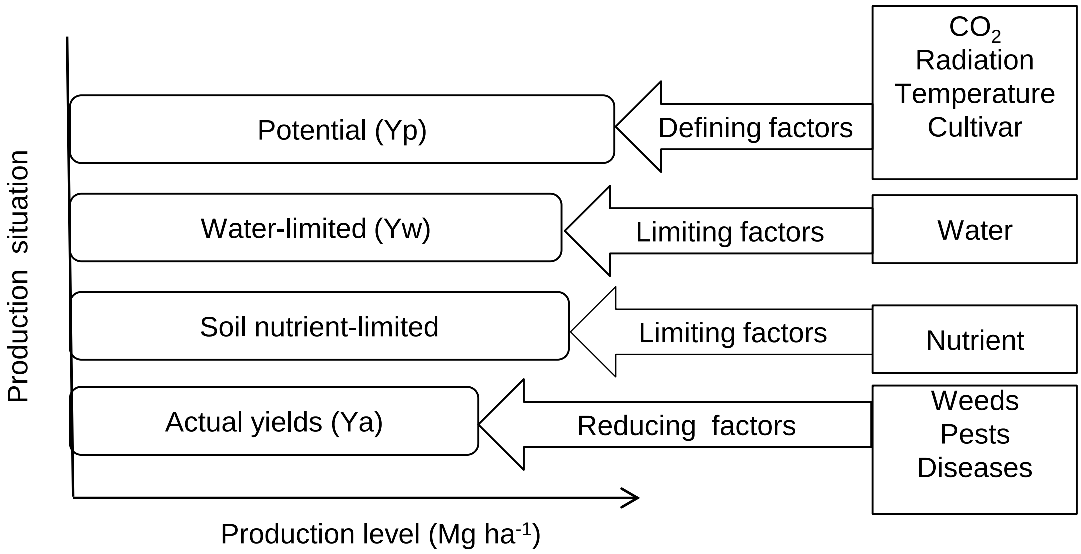


Figure 1.2. Different production levels as determined by growth defining, limiting and reducing factors. Source: van Ittersum et al. (2013).

1.4. Importance of processing potato

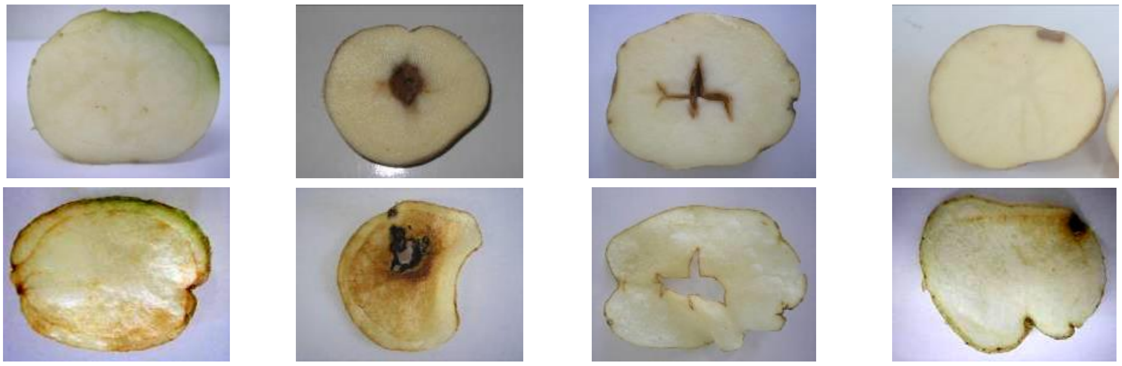
Global consumer demand for potato continue to change from fresh to value added processed products due to rising incomes and urbanization (Wang et al. 2012; De Jong 20169. And also, the diversification of diets and increase in number of women in the labor force that leaves less time for preparing fresh product for consumption (FAO 2008; Guenthner 2010). The growth has been driven by increasing demand from fast food industry for frozen and processing products (De Jong 2016).

Potatoes for chip processing must satisfy stringent quality requirements for suitability for processing and also ability to produce products that meet expectations of a consumer. Tuber size, dry matter content, low reducing sugars and low physiological defects form basic criteria for selecting potatoes suitable for processing (Burke et al. 2005). In addition, optimizing tuber size and quality are important to maximizing finished product yield and profits for both growers and industry (Bussan et al. 2007). In Hokkaido region, potato sizes ranging from 60 to 340 g are required for chip processing (Murakami 2012). Uniform size distribution of potato tubers is important because it facilitates mechanical removal of peels more efficiently and with minimum loss. In contrast, wide variation in size requires size grading at the factory and in some cases cutting the large ones for efficiency in processing that lead to economic loss to both growers and processors (Gould 1999).

Chip processing industry requires tubers with high specific gravity because it is associated with high product yield per unit fresh weight compared to tubers with low dry matter content (Burton et al. 1992). In addition, high specific gravity tubers require less energy input during frying or dehydration to remove water and generally produce products with better texture (Mosley and Chase 1993). For this reason, specific gravity is considered an excellent indicator of potato tuber dry matter content and final product quality. Although specific gravity is primarily associated with cultivar, it is also influenced by soil mineral nutrition during growing season. For example, excessive N fertilizer has been shown to promote vegetative growth and lowers yields and dry matter content reduced yield and dry matter (Abdalla et al. 1995; Vos 1997). Nitrogen is also associated with increased Gibberellin biosynthesis, and high Gibberellin levels inhibit tuberization (Abdalla et al. 1995) and impede accumulation of starch in tubers (Vreugdenhil and Sergeeva 1999). Conflicting results of excess K application on quality and yield have been reported. Allison et al. (2001b) and Kang et al. (2014) found a decrease in potato yield and tuber specific gravity with increasing levels of K fertilizer, while AbdelGadir et al. (2003) did not observe any change. Other studies observed that K in the form of KCl lowered specific gravity more than K_2SO_4 (Kumar et al. 2007; Westermann et al. 1994).

Potato tubers are mainly made up of parenchymatous cells and lacks specialized secondary thickened tissues (McGarry et al. 1996). For this reason, potatoes are susceptible to various forms of damage during harvest, handling, storage and marketing operations. Bruising is one of the major causes of quality loss in tuber quality (Fig. 1.3) and market value resulting in economic loss to growers and processor and growers may lose in excess of 20% (Storey and Davies 1992; Corsini et al. 1999). While it is a simple matter to grade out tubers showing external damage, internal damage such as black spot bruise is not visible until after peeling (McGarry et al. 1996).

Bruising occur as a result of a mechanical impact that damages intra-cellular membranes (Corsin et al. 1992). This allows phenols to come into contact with polyphenol oxidase (PPO) that consequently produces melanin that causes dark pigment. Development of blackspot bruise depends on the mechanical impact and susceptibility of tubers to an impact (Corsini et al. 1999). Structural properties of tubers influence its resistance to blackspot bruise (Laerke et al. 2002).



Greening Brown center Hollow heart Blackspot bruise

Figure 1.3. Photographs of the chip products made from potatoes with physiological defects before and after frying.

Past studies have shown the role of Ca in reducing blackspot bruise (Karlson et al. 2006; Palta 2010). Ca strengthen cell wall and membrane structure (Palta 1996), and Ca in the tissue influences biochemical aspects of tissues (Mapson et al. 1963). Biochemically, blackspot bruise is accumulation of melanin following injury of cells resulting in black pigment (Corsin et al. 1999). Ca reduces the level of free tyrosine and phenolase present in tuber tissues that are associated with bruise formation (Mapson et al. 1963). Ca can also regulate polyphenols lead biochemically to melanin formation (Stark et al. 1985). Additionally, Ca act as a secondary messenger controlling the functions of enzymes and cellular metabolism (Palta 1996). For this reason, Ca is considered to be crucial element in improving the quality of processing potatoes.

Maintaining low reducing sugar levels is necessary to obtain desirable color and flavor that are among the important qualities for potato chips and presents processing industry with a biggest problem (Stevenson et al. 1964). Generally, yellowish brown (Burton et al. 1992), uniform light golden (Stevenson et al 1964) and lighter colored chips (Cunningham and Stevenson 1963) are preferred. However, high reducing sugars in potato tubers lead to undesirable color and flavored products) that occur as a result of Maillard reaction between reducing sugars (glucose and fructose) in tubers and amino alpha groups of free amino acids. This compromise chip quality and commercial value of tubers, and excess sugars may makes tubers unfit for chip processing (Chapper et al. 2002).

1.5. Objectives of the study

Although Hokkaido is an important place with respect to potato production in Japan, its yield is quite low compared to major world potato producing countries like USA, New Zealand (FAO 2016). Given the availability of suitable climatic and edaphic conditions for potato production in Hokkaido, consumer demand for processing potatoes, and the desire for self-sufficient in potato production, there is need to increase potato productivity. Understanding the influence of abiotic factors that determine and limit yields is important to guide formulation of good management practices. And also, the knowledge of the yield levels and how they are established as an interaction between genotype and environment may help establish the role of cultivars, environments and agronomic practices that can guide formulation of better management practices to enhance production.

Chip processing industry require bruise-free and high specific gravity tubers for good quality products (Barietelle and Hyde 2003). However, there may be a conflict in achieving these goals because high specific gravity tubers are easily bruised due to high starch granules that increases the potential of physical damage to the membrane (Corsin et al. 1999). Past studies have provided evidence of the role of Ca to mitigate incidences of blackspot bruise (Karlsson et al. 2006). There is lack of information about the status of soil exchangeable Ca in potato producing fields of Hokkaido. And, also the status of physiological defects in potatoes and its relationship with Ca is unknown. Furthermore, the status of other macronutrients in the soil and their effects on potato yield and quality are also not fully understood.

Therefore, the overall goal of this study was to improve yield and quality of processing potato in Hokkaido, Japan. To achieve this goal the study had the following objectives;

(i) to understand the performance of yield and quality characteristics of processing potato cultivars under grower management conditions in two contrasting soil types

(ii) to assess the influence of available soil nutrients and in-season NPK application on yield, quality, and nutrient composition of potato tubers.

(iii) to understand the effects of soil and potato tuber Ca content on quality of potato tubers.

(iv) to evaluate the effects of slope direction on soil properties and potato yields.

CHAPTER 2. GENERAL INFORMATION AND SAMPLING DESIGN

2.1. Site description

2.1.1. Location

Hokkaido, Japan`s northern most island is the major potato producing region that accounts for 80% of country`s total production. Potato is grown as a summer crop in Hokkaido and planting start anytime in late spring, after the ground is thawed, and are harvested from August to October. The major potato producing areas in Hokkaido prefecture are Tokachi, Abashiri, Shiribeshi and Kamikawa districts. This study was conducted in Tokachi and Kamikawa districts in 2013 and 2014 growing seasons. The two districts were purposely chosen for this study because they are among the major potato producing districts in Hokkaido, accounting for 41 and 6% of the total production in Hokkaido, respectively (MAFF 2016). Soil and potato plant tuber samples were collected from 90 and 80 fields (Fig.2.1) in Tokachi and Kamikawa districts, respectively.

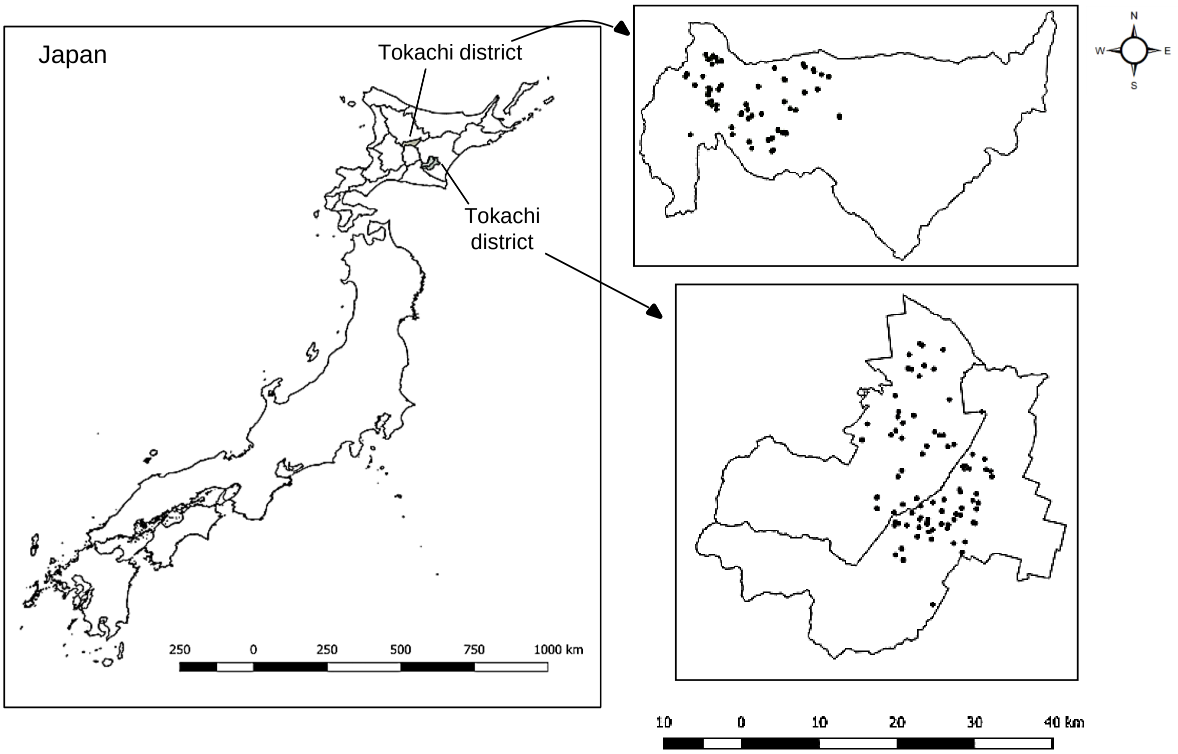


Figure 2.1. Map of Japan showing location of Tokachi and Kamikawa districts. Points indicate the sampling sites of soil and potato samples in each study area collected in 2013 and 2014 growing seasons.

The selected fields were representative of average potato growing fields in the region with a range of management histories.

2.1.2. Soil types

The second reason for selecting Tokachi and Kamikawa district as study sites was because of their differences in soil characteristics due to but not limited by the factors affecting their soil formations. Although 35% of arable soils in Hokkaido are of volcanic origin, Tokachi district is predominantly covered by volcanic ash soils accounting for 57% of the total arable area in the district (Hashimoto 2008). Majority of the soils are classified as Andosols according to the Classification of Cultivated Soils in Japan (Cultivated Soil Classification Committee 1995) followed by lowland soils around the river system. In contrast, Kamikawa district is primarily dominated by upland soils of pyroclastic flow deposit origin. These soils readily form crusts upon drying and have a remarkably high solid percentage, especially in higher elevation fields.

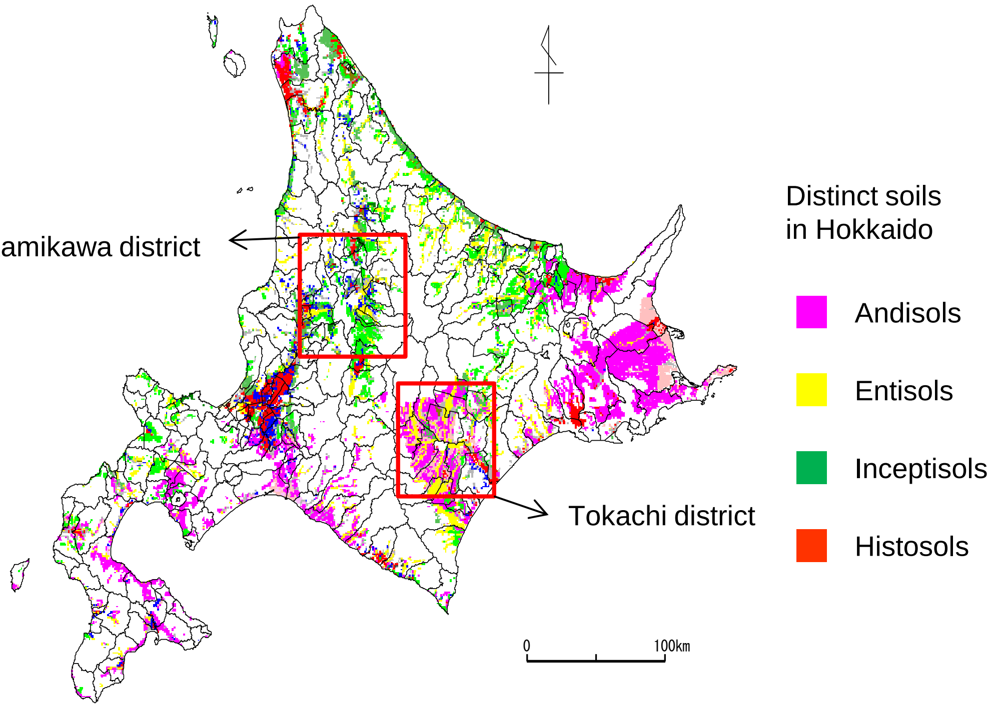


Figure 2.2. Soil map of arable land in Hokkaido. Two red rectangles indicate positions of Tokachi and Kamikawa districts on the map.

(Source: Hokkaido Research Organization Central Agricultural Experiment Station)

The majority of these three soil classes, Andosols, Lowland soils and upland soils are equivalent to Andisols, Entisols and Inceptisols, respectively, according to the Soil Taxonomy of the United States Department of Agriculture (Soil Survey Staff 2014). The soils are favorable for upland crops because of good drainage necessary for optimum growth permeability.

2.2. Processing potato cultivars

Four potato processing cultivars thus Andover, Toyoshiro, Kitahime, and Snowden that are used and/or bred for potato chip production in Hokkaido region were purposely selected for this study because they are among the popular cultivars grown in Hokkaido. These cultivars were classified based on length of maturation period as early to medium (60 to 95 days), medium early (95 to 125 days), and medium late (125 to 135 days; Lisinska and Leszczynski 1989). Andover is an early to mid-season tablestock and chip cultivar developed from a cross between Allegany and Atlantic (Fig. 2.3).

Figure 2.3. Photographs of potato tuber and flowers of Andover cultivar.

In Hokkaido region, it performs as an early maturing cultivar. It has a very rapid emergence and early tuber set but very susceptible to drought and heat stress that cause early senescing and reduce late season yield (Plaisted et al. 1998). It is resistant to common scab (*Streptomyces scabies*), powdery scab and golden cyst nematode (*Globodera rostochiensis*). Since Hokkaido has a short growing season, the cultivar is ideal for crop rotation because it allows farmers to have sufficient time for preparation of fields for the next crop (often winter wheat).

Figure 2.4. Photographs of potato tuber and flowers of Toyoshiro cultivar.

Toyoshiro is a mid-season cultivar that was selected from a cross between Eniwa and Hokkai 19 (Fig. 2.4). Currently, it is a leading processing cultivar in Japan, popular for producing good quality chips and high tuber yields (Sato et al. 2017). It accounts for over 11% of the total area planted for processing cultivar in Japan (Deguchi et al. 2016). However, the cultivar is susceptible to Early blight (*Alternaria solani*), golden nematode and common scab.

Kitahime is a mid-season cultivar that was selected from a cross between Sayaka and White frier (Fig. 2.5). It is known for possessing genetic potential to control starch-sugar interconversion when stored at low temperatures for a prolonged time. It is also resistant to potato cyst nematode but susceptible to Early blight disease and common scab (Ogawa 2012).

Figure 2.5. Photographs of potato tuber and flowers of Kitahime cultivar.

Snowden is a chip processing cultivar that was selected from a cross between B514-6 and Wischip in USA (Fig. 2.6; Love and Thompson 1999). The cultivar performs as a late season cultivar that matures in more than 150 days. Just like Kitahime, it has low reducing sugar content under low storage temperatures. It is regarded as one of the standard chip potato cultivar in the USA (Hutchinson et al. 2003). In Japan, it is also predominantly used to produce good quality potato chips. It is susceptible to Early blight, Late blight, and common scab.

Figure 2.6. Photographs of potato tuber and flowers of Snowden cultivar.

2.3. Crop management

2.3.1. Crop rotation

Potato crop in the region is grown under non-irrigated conditions, and planted in late spring (between April and May) after the ground is thawed, and harvested between August and October to meet the market window before winter season.

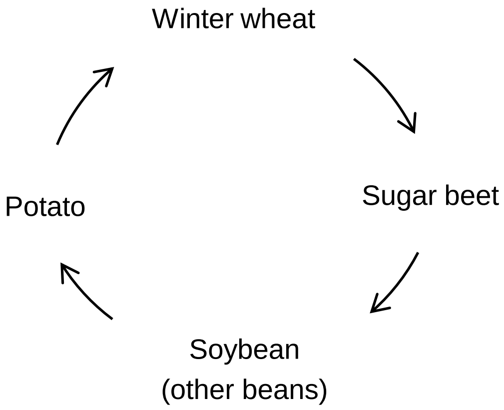


Figure 2.7. Crop rotation system followed in Hokkaido region.

(Department of Agriculture, Hokkaido Government 2015)

Growers in this region typically practice a four-year rotation (Fig. 2.7) of potato, winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L.), and soybean (*Glycine max* L.), in which winter wheat is often planted just after potato cultivation. In this study, different potato fields were used as study sites each year because of crop rotation adopted in Hokkaido region. During the two year period of our study, 50 and 40 fields used in this study were planted with soybeans and sugar beet, in the previous season in Tokachi district, respectively. Similarly, in Kamikawa district, 32 and 29 fields used in this study were planted with sugar beet and winter wheat, in the previous season, respectively.

2.3.2. Ridging systems

In Hokkaido, either early season ridging system or conventional ridging sysyem are often practiced depending on the soil type. Under early ridging system, potato seed tubers are first planted at the depth of about 10 cm and spaced at 30 cm within rows and 75 cm between rows. Hilling is performed before emergence once within two weeks after planting before the potato crop emergence using a tractor (Fig. 2.8a).

Under conventional ridging system hilling is made three times between end-May and mid-June after seed germination (Onami 2002). First hilling is done by pilling up soils to a height of approximately 5 cm. The second hilling is done approximately 30 days after emmergence when plants are about 25 cm high. This is done by earthing up the soil around the vines base to about 20 cm high (Fig 2.8b).

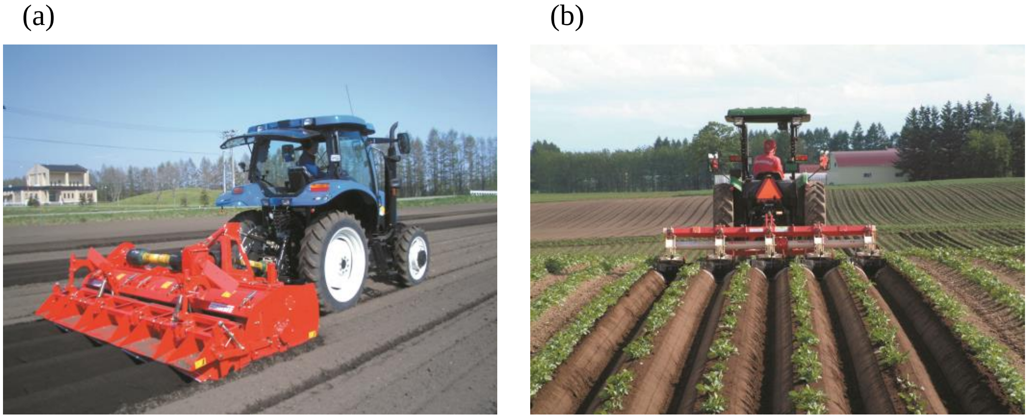


Figure 2.8. Photographs showing (a) early season ridge making and (b) conventional ridge making in Hokkaido.

2.3.3. Hokkaido fertilizer recommendation

Current fertilizer application guidelines in Hokkaido are based on crop type, cultivar, cultivation method, region, and soil class and soil tests results. Soil test is the common method for assessing the amount of plant available nutrients in soils and determining the need for nutrient additions to meet crop needs in Hokkaido. The assumption is that crop response to fertilizer applications occurs when soil test levels are below established levels. And, the lower the test value is below the critical level, the higher the probability of response to added fertilizer and the higher the fertilizer required to achieve optimum yield. It is also assumed that crop response to fertilizer application diminishes as soil test values increases. Different countries use different methods for routine evaluation of soil available nutrients. In Hokkaido region, soil available N, P, and K status in upland fields of Hokkaido are evaluated using hot water extraction method, Truog method and ammonium acetate extraction method, respectively.

All fertilizer is applied at planting in a band where the hill would be formed and then roto-tilled into the soil. Generally, fertilizer is concentrated in a strip approximately 20 cm wide and 10cm deep prior to planting. For each soil type, a base standard fertilizer application rates has been established (Table 2.1; Department of Agriculture, Hokkaido Government 2015), and growers are required to either add on or subtract from the base rate depending on the soil test results. Growers are required to apply fertilizer rates based on soil test results. Although Hokkaido Fertilizer Recommendation provides guidelines for optimal soil available nutrients (Department of Agriculture, Hokkaido Government 2015), there is no provision for Ca fertilization to supplement soil Ca levels.

Table 2.1. Location, soil type, standard fertilizer recommendations in Tokachi and Kamikawa districts.

			Standard fertilizer rates (kg ha^{-1})[a]		
Location	Soil type	Number of sites	N	P_2O_5	K_2O
Tokachi	Andisols	78	60	200	110
	Lowland soils	12	50	140	100
Kamikawa	Upland soils	72	80	180	110
	Lowland soils	8	50	140	100

[a]Standard fertilizer application rates recommended by Hokkaido Fertilizer Recommendations (Department of Agriculture, Hokkaido Government 2015). The major sources of N, P, and K fertilizers used in the two regions are ammonium sulfate, mono ammonium phosphate and potassium sulfate, respectively.

As a result of different soil types found in Tokachi and Kamikawa districts, different standard fertilizer rates are recommended for potato production as shown in Table 2.1.

2.4. Climatic conditions of the study period (2013-2014)

Cumulative precipitation between May and August for Tokachi district was 337 and 445 mm in 2013 and 2014, respectively (Table 2.2), and the latter was equivalent to the 10 year average (407 mm). In Kamikawa district, total precipitation received in 2014 was 1.6 times more than 2013 growing season, and was higher than 10 year average (431 mm; Table 2.2). Temporal precipitation distribution differed between the two years. In 2014, 46% of precipitation fell during the critical tuber bulking period (June and July) whereas 25% was received during the same period in 2013. Prior to planting, Kamikawa district received heavy rains in 2013 that delayed planting of potatoes by two to three weeks.

2013 was a warm year for Tokachi with the mean air temperature between May and August 2.1°C higher than the 10 year average of 16.8°C (Table 2.2), whereas in Kamikawa district, the mean air temperature was 1.2 °C lower than the 10 year average of 18.0°C. Shorter sunlight hours were observed in the spring of 2013 in Kamikawa district that delayed planting for two to three weeks.

Table 2.2. Weather conditions for Tokachi and Kamikawa districts for the growing period (May to August) as well as long term average weather conditions (2005 to 2014).

Location	Year	Precipitation (mm)	Sunlight hours	Mean temperature (°C)
Tokachi	2013	337	518	18.4
	2014	445	616	18.9
	2005 - 2014	407	587	16.8
Kamikawa	2013	368	718	16.8
	2014	613	772	17.7
	2005 - 2014	431	702	18.0

Japan Meteological Agency (2018).

2.5. Soil and potato tuber sample collection

On each of the selected study fields, a sampling plot of 5-m row length was established where plant stand was relatively uniform (no missing plant). Global position system (GPS) device was used to record the sampling locations, and GPS data was later used to determine topographic variables of each site. The size of each selected plot was three rows wide and 15 plants long, with a 75 cm row spacing (ranged between 73 and 93 cm) and 30 cm plant spacing (ranged between 19 and 42 cm). To minimize the likelihood of border effects, the sampling plot was placed at least 3 m away from the boundary and tractor paths to avoid border effects. Areas close to the ditches and manure dumps were also avoided.

As a result of the crop-rotation sequences, different potato study fields were used each year. Potatoes were preceded by soybean and sugar beet in Tokachi district, and sugar beet and winter wheat in Kamikawa district. Soil samples were collected at flowering stage from two side rows (Fig. 2.10).

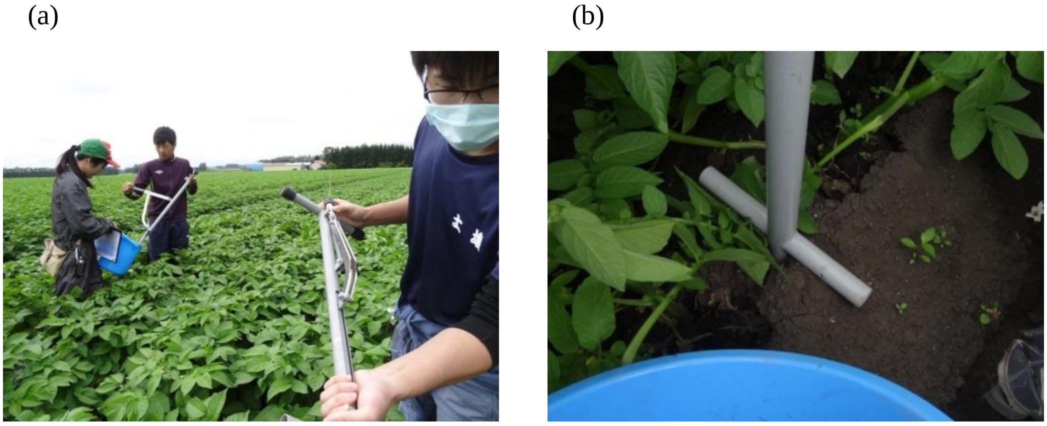


Figure 2.9. Photographs of (a) soil sampling during flowering stage and (b) soil sampling locations relative to the potato crops.

Ten sub-samples (5 samples from each row) were collected from 0-to-20 cm depth between the plants. Because ridge soil has been shown to represent the soil environment where crop plants have access to, furrow soil not sampled. The collected soil samples were thoroughly mixed and composited into one single soil sample. Collected samples were put in a zipped polyethylene bags and transported to the laboratory for chemical analysis.

Potato tubers were harvested by hand (Fig. 2.11a) by carefully lifting the plant and gently separating the tubers from plant. Then dig into the side of the hill and lift up to collect the tubers. All potato tubers from the selected 15 plants were harvested. In total four cultivars; Toyoshiro (n = 50), Snowden (n = 50), Kitahime (n = 40) and Andover (n = 30) were sampled. For measurement of yield and yield components, stems were counted in the middle row, and tuber number and weight were obtained after harvesting all tubers in the 5-m row by hand. Stems (mainstems) were counted at harvest to ensure accurate determination of stem number due to tendency of potato to branch underground. Tubers greater than 20 g were harvested and weighed to obtain total yield per plot. Tuber number per plant was then calculated by dividing the number of tubers by number of plants. The length of the selected plot and row width were used to calculate stem and tuber density.

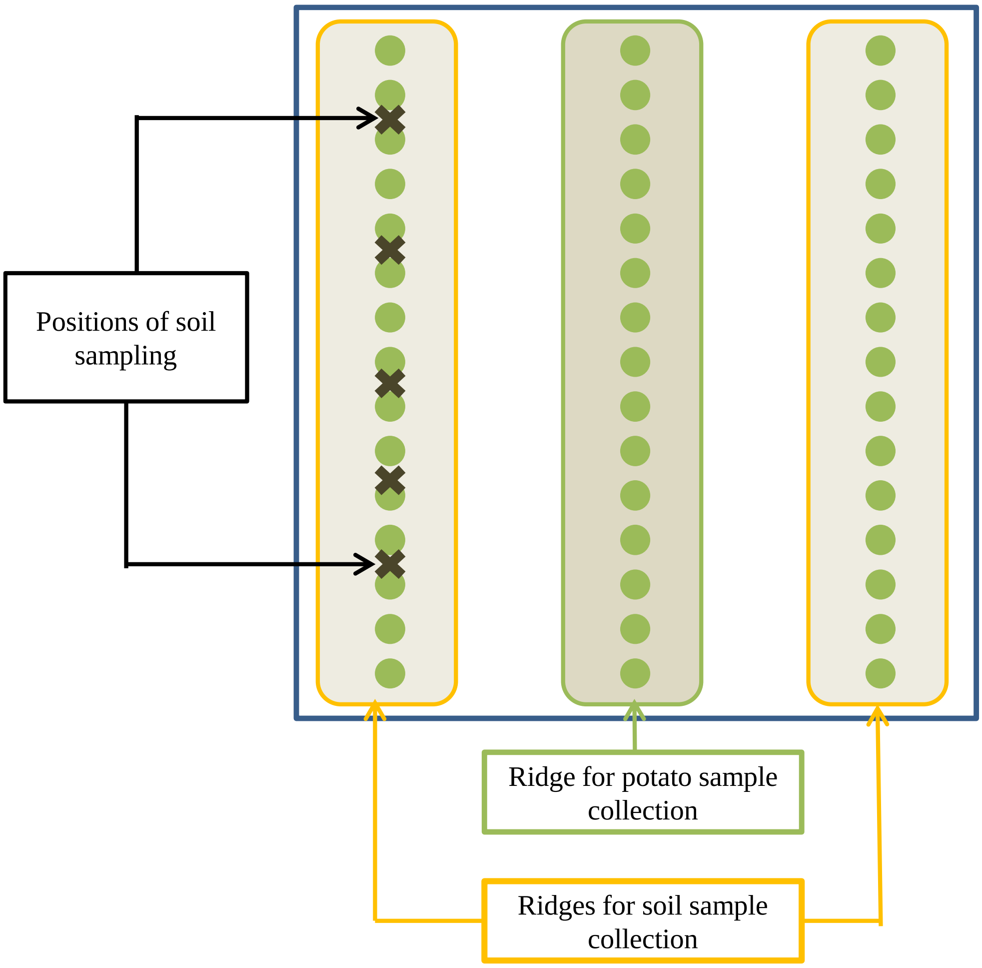


Figure 2.10. Schematic representation of potato ridges showing positions of soil and potato tuber sample collection.

Potato tuber specific gravity was determined by the hydrometer method on a 3-kg subsample of marketable potatoes per field (Edgar 1951). We also conducted interviews to understand growers' management strategies.

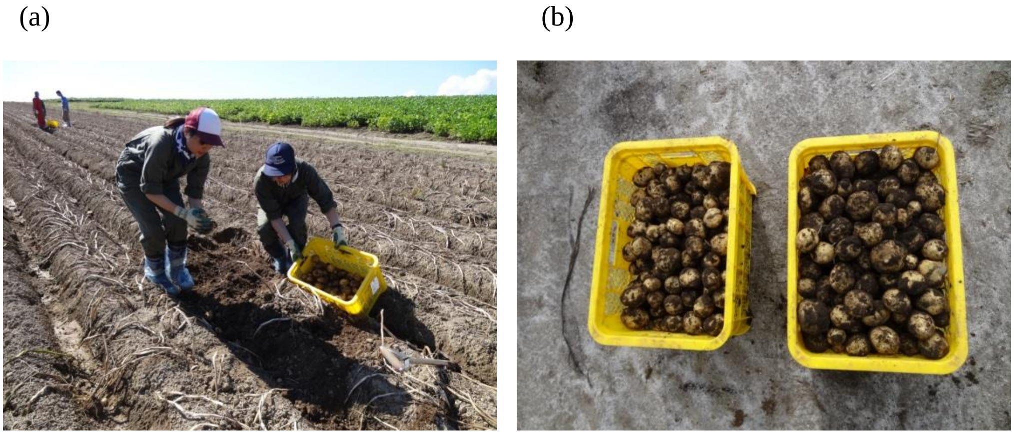


Fig. 2.11 Photographs of (a) the harvesting of potatoes by hand, and (b) the harvested potatoes.

CHAPTER 3. YIELD AND QUALITY CHARACTERISTICS OF PROCESSING POTATO CULTIVARS UNDER GROWERS' MANAGEMENT

3.1. Abstract

Consumer demand for processing potatoes is increasing in Japan owing to change in eating habits from fresh potatoes to processed products, however, the country is not self-sufficient in potato production. Understanding potato crop and soil factors that limit yields can guide formulation of better management practices. In present study, paired soil and tubers samples were collected from 170 sites to evaluate the performance of four processing cultivars under growers' management conditions. Tuber yields and yield components (stem number per plant, tuber number per plant, and mean tuber weight) were measured. The results indicated: (1) yield components and yield were influence by cultivar and soil types. Stem number can affected tuber number and tuber number in turn influenced tuber size. Growers need to optimize marketable yield by regulating number of stem. (2) For some cultivars starch yield was also affected by soil type, growers need carefully select cultivars adapted to a given locality to maximize marketable yield and processing quality. (3) Large variation in total tuber yields (from 21.9 to 68.2 Mg ha^{-1}) that suggested possibility of increasing potato yields with proper agronomic practices.

Key words: Mean tuber weight, Stem number, Tuber number, Tuber yield

3.2. Introduction

Japan produces 2.2 million tons of potato (*Solanum tuberosum* L.) annually on 79,700 ha of land (MAFF 2016), a much lower productivity than most developed countries such as USA (FAO 2016). Yield potential of potato can reach up to 77 tons ha^{-1} (Deguchi et al. 2016), revealing that there is possibility to further improve current potato production in Japan. Although potatoes are produced in all parts of Japan, 80% of the nation's production comes from Hokkaido, the northernmost region of Japan. Twenty-four percent of the nation's annual production is used in processing industry (GAIN 2014), and the consumer demand has been shifting from fresh potatoes to processed products (Mori et al. 2015). However, the domestic supply has not changed for the past five decades (FAO 2016), and fresh potato tubers cannot be easily imported because of phytosanitary regulations. Additionally, area under potato cultivation is decreasing, as a result the country is not self-sufficient in potato and substantial proportion of potato products consumed in the country is imported (Nagatomo 2012; Deguchi et al. 2016). The rising demand for processing potatoes in Japan and the existing yield gaps in the farm lands requires further attention to guide formulation of management practices to improve the productivity.

For processing potato production, optimizing both tuber yield and quality are important to maximizing finished product yield and profits for both growers and industry (Bussan et al. 2007). Physiologically, tuber yields in potatoes are a product of three yield components: number of stems, number of tubers per stem, and mean tuber weight (Del Morena et al. 1994). Early studies in the United Kingdom demonstrated that total tuber yields and proportion of different grade sizes depend on number of main stems per unit area (Bleasdale 1965). This and together with some others have shown that tuber yield increases in proportion to stem numbers (Collins 1977; Bussan et al. 2007). However, a study with seven cultivars suggested stem number per unit area to be a poor predictor of total and marketable yield and suggested to use tuber number per mainstem as an early season predictor for yield (Lynch et al. 2001). Furthermore, recent study (Zelalem et al. 2009) noted that total tuber yield was strongly associated with both average tuber weight and total tuber number that signified the importance for increasing both of the factors concurrently for improving yields. Tuber size distribution is important economic considerations in potato industry in order to maximize crop value. Different pay scales exist according to tuber sizes across potato markets, and growers often receive premiums for tubers meeting specific size (Bussan et al. 2007). For chipping, specific size requirement exists, and marketable sized tubers in Hokkaido region range from 60 to 340 g (Murakami 2012). Increases in stem numbers have been frequently associated with increases in yields of undesirable, undersized tubers. Inter-tuber competition for available resources of light, water and nutrients result in reduced tuber sizes (Moorby 1967).

Desired quality in produced potato depends upon the final product (Harris 1992). For processing into chips, specific gravity is a principle quality characteristic used for assessing acceptability of tubers as it reflects the dry matter content (including starch content) of the tubers (Kleinkopf et al. 1987). High specific gravity tubers are desired as they result in greater product yield per unit fresh mass and generally produce products with better texture (Mosley and Chase 1993).

Apart from cultivar, studies have shown that yield components can also be influenced by chemical properties of the soil. Maier et al. (2002) and Rosen and Bierman (2008) reported a significant increase in stem number per plant with P fertilization that was accompanied by increase in number of tubers per stem. Furthermore, Rosen and Bierman (2008) found that an increase in tuber number per plant was associated with an increase in the number of undersized tubers. Other studies have found that Ca application can result in a decrease in the number of tubers per plant and an increase in tuber size (Ozgen and Palta 2005). Krauss (1985) demonstrated that application of high rates of N fertilizer to potato plant inhibit tuberization.

Although many studies have been done on the interrelationships between yield components and ultimate yield of potatoes, little has been reported on the performance evaluation of processing potato cultivars under grower field conditions. Also, many potato cultivars are developed under environments which differ from those in the target production region. Present studies evaluated the yield components of four major cultivars under two contrasting soil types. Therefore, information on the consistency of cultivar performance across soil types and growing seasons is important to breeders and growers. The objectives of this study were to i) evaluate the performance of four major processing potato cultivars under variable soil-environmental and weather conditions and farmer management conditions and ii) determine both cultivar traits and environmental factors important to optimizing both yield and quality concurrently. iii) Since soil properties are drastically different in two regions of the study, our study explored soil and yield components in relation to soil nutrient availability especially N, P, and Ca.

3.3. Materials and Methods

3.3.1. Study sites

A two-year soil and potato plant survey (2013 and 2014) was conducted in 90 and 80 fields with variable management histories in Tokachi and Kamikawa districts, respectively. The study was done in two years and two different districts to provide differences in soil type and growing seasons representative of major potato growing areas of Hokkaido as described in chapter two.

3.3.2. Crop management

Potato crop in the region is grown under non-irrigated conditions, and planted in late spring (between April and May) after the ground is thawed, and harvested between August and October to meet the market window before winter season. As far as we know the growers use uncut seed pieces for establishing commercial fields. Growers in this region typically practice a four-year rotation of potato, winter wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L.), and soybean (*Glycine max* L.), in which winter wheat is often planted just after potato cultivation. As a result of different soil types found in the two regions, different standard fertilizer rates are recommended for potato production. The standard fertilizer rates of 60 kg N ha^{-1}, 200 kg P_2O_5, and 110 K_2O are recommended in Tokachi district while in Kamikawa district 80 kg N ha^{-1}, 180 kg P_2O_5, and 110 K_2O are recommended for processing potatoes (Department of Agriculture, Hokkaido Government 2015). We selected four major processing potato cultivars used and/or bred for potato chip production in Hokkaido region for this study that are Andover, Toyoshiro, Kitahime, and Snowden. These cultivars were classified based on length of maturation period as early to medium (60 to 95 days), medium early (95 to 125 days), and medium late (125 to 135 days; Lisinska and Leszczynski 1989).

Andover is an early to mid-season tablestock and chip cultivar developed from a cross between Allegany and Atlantic. In Hokkaido region, it performs as an early maturing cultivar. It has a very rapid emergence and early tuber set but very susceptible to drought and heat stress that cause early senescing and reduce late season yield (Plaisted et al. 1998). Since Hokkaido has a short growing season, the cultivar is ideal for crop rotation because it allows farmers to have sufficient time for preparation of fields for the next crop (often winter wheat).

Toyoshiro is a mid-season cultivar that was selected from a cross between Eniwa and Hokkai 19. Currently, it is a leading processing cultivar in Japan, popular for producing good quality chips and high tuber yields (Sato et al. 2017). It accounts for over 11% of the total area planted for processing cultivar in Japan (Deguchi et al. 2016).

Kitahime is a mid-season cultivar that was selected from a cross between Sayaka and White frier. It is known for possessing genetic potential to control starch-sugar interconversion when stored at low temperatures for a prolonged time.

Snowden is a chip processing cultivar that was selected from a cross between B514-6 and Wischip in USA (Love 1999). The cultivar performs as a late season cultivar that matures in more than 150 days. Just like Kitahime, it has low reducing sugar content under low storage temperatures. It is regarded as one of the standard chip potato cultivar in the USA (Hutchinson et al. 2002). In Japan, it is also predominantly used to produce good quality potato chips.

3.3.3. Climatic conditions of the study period

Cumulative precipitation between May and August for Tokachi district was 337 and 445 mm in 2013 and 2014, respectively (Table 3.1), and the latter was equivalent to the 10 year average (407 mm). In Kamikawa district, total precipitation received in 2014 was 1.6 times more than 2013 growing season, and was higher than 10 year average (431 mm; Table 3.1). Temporal precipitation distribution differed between the two years. In 2014, 46% of precipitation fell during the critical tuber bulking period (June and July) whereas 25% was received during the same period in 2013.

Prior to planting, Kamikawa district received heavy rains in 2013 that delayed planting of potatoes by two to three weeks.

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	2014	613	772	17.7
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Japan Meteological Agency (2018).

3.3.4. Potato and soil sampling design

On each of the selected study fields, a sampling plot of 5-m row length was established where plant stand was relatively uniform (no missing plant). The size of each selected plot was three rows wide and 15 plants long, with a 75 cm row spacing (ranged between 73 and 93 cm) and 30 cm plant spacing (ranged between 19 and 42 cm). The sampling plot was placed at least 3 m away from the boundary and tractor paths to avoid border effects. Areas close to the ditches and manure dumps were also avoided. As a result of the crop-rotation sequences, different potato study fields were used each year. Potatoes were preceded by soybean and sugar beet in Tokachi district, and sugar beet and winter wheat in Kamikawa district.

Soil samples were collected at flowering stage from two side rows. Ten sub-samples (5 samples from each row) were collected from 0-to-20 cm depth between the plants. The collected soil samples were thoroughly mixed and composited into one single soil sample.

Four potato cultivars were sampled; Toyoshiro (n = 50), Snowden (n = 50), Kitahime (n = 40), and Andover (n = 30). For measurement of yield and yield components, stems were counted in the middle row, and tuber number and weight were obtained after harvesting all tubers in the 5-m row by hand. Stems (mainstems) were counted at harvest to ensure accurate determination of stem number due to tendency of potato to branch underground. Tubers greater than 20 g were harvested and weighed to obtain total yield per plot. We calculated marketable yield from tubers weighing from 60 to 340 g. Because of different maturation period, harvesting was not done at the same time. Andover being an early maturing cultivar was harvested at least 7 days before Toyoshiro and Kitahime cultivars and Snowden was harvested two weeks later. The tuber number per plant was then calculated by dividing the number of tubers by the number of plants. The length of the selected plot and row width were used to calculate stem and tuber density. Potato tuber specific gravity was determined by the hydrometer method on a 3-kg subsample of the marketable potatoes per field (Edgar 1951). The calculations of starch content in tubers were adapted from the approach outlined by Takada (2012), who recommended that starch content in tubers could be estimated by;

$$\text{Starch Value (\%)} = 214.5 \times (\text{specific gravity} - 1.05) + 7.5 \qquad \text{(Eqn 3.1)}$$

and further determining starch content;

$$\text{Starch yield (Mg ha}^{-1}\text{)} = \text{Tuber yield (Mg ha}^{-1}\text{)} \times (\text{starch value} - 1.0)/1000 \qquad \text{(Eqn 3.2)}$$

3.3.5. Soil analyses

Soil samples were air dried and passed through a 2-mm sieve before chemical analysis. The cation exchange capacity (CEC) was measured by using ammonium acetate extraction method buffered at pH 7 as described by Schollenberger and Dreibelbis (1930). The Ca and K concentration in the ammonium acetate extract was quantified by atomic absorption spectrophotometer (AAS; Z-5010, Hitachi Corporation, Tokyo, Japan). Water soluble Ca was measured by shaking 1: 5 soil/water solution for one hour, and quantified by AAS. Available N was determined by hot water extraction method because it is the recommended method for routine evaluation for making N fertilizer recommendation in Hokkaido (Department of Agriculture, Hokkaido Government, 2015). For this analysis, N was measured by heating 1:10 soil/water solution in an autoclave at 105°C for one hour (Cutin et al. 2006), and N was quantified by total organic carbon analyzer (TOC-VCPH TNM-1, Shimadzu Corporation, Kyoto, Japan). Soil-available phosphate was estimated using the Truog method (Truog 1930). For this analysis, 0.5 mmol L^{-1} sulfuric acid (H_2SO_4) and ammonium sulfate ($(NH4)_2SO_4$) at pH 3 were used. The phosphate concentration in the filtrate was quantified by the colorimetric molybdate blue method developed by Murphy and Riley (1962). Phosphate absorption coefficient (PAC) was estimated based on the phosphate retained by the soil after equilibrium using a 2.5% diammonium phosphate solution, and measured by the colorimetric molybdate yellow method (Nanzyo 1997). Phosphate absorption coefficient values determined by this procedure have been used extensively in Japan as an index of soil`s capacity to make phosphate unavailable to crop. Total carbon (TC) content was assessed on grounded samples and the measurement was undertaken using a dry combustion method with a Vario EL III analyzer (Elementar Analysensysteme, Hanau, Germany). Acid-oxalate extractable aluminum (Al_o) was determined using a 0.2-mol L^{-1} acid ammonium oxalate solution (pH 3) at a soil/solution ratio of 1:100 for 4 h equilibration in the dark (Blakemore et al. 1987), followed by measurement of aluminum concentration by inductively coupled plasma atomic emission spectroscopy (ICP-AES, ICP-8100, Shimadzu Corporation, Kyoto, Japan).

3.3.6. Statistical analyses

Statistical analyses were carried out using Excel Statistics 2012 (Social Survey Research Information, Tokyo, Japan). Descriptive statistics for tuber yields and yield components (stem number per plant, number of tubers per plant, and mean tuber weight) were calculated. Analysis of variance (ANOVA) was completed on the main effects and interaction effects, effects were considered significant at 0.05 probability level. Significant mean was tested using Tukey’s honest significant difference (HSD) test (α = 0.05). Pearson correlations were performed to determine the extent of relationships among stem number per plant, number of tubers per plant, and mean tuber weight. Box plots were used to describe variation in total potato tuber yields and starch content within and among the processing cultivars in Tokachi and Kamikawa districts.

3.4. Results and discussion

3.4.1. Soil and potato crop characteristics in Tokachi and Kamikawa districts

The detailed soil classification of the soils for each of the study fields was described in Gondwe et al. (2017). Generally, inherent characteristics (TC, CEC, PAC and Al_o) of soils from Tokachi and Kamikawa districts were distinctly different (Table 3.2). Soils in the Tokachi district were more than twofold higher in organic matter (TC) and CEC as compared to Kamikawa district.

Table 3.2. Mean values of soil and potato crop characteristics of samples collected from Tokachi and Kamikawa district.

Soil/plant property	Unit	Tokachi		Kamikawa	
Total carbon	g kg^{-1}	49.8	a	17.0	b
Cation exchange capacity	$cmol_c$ kg^{-1}	27.7	a	13.8	b
Acid-oxalate extractable aluminum	g kg^{-1}	35.3	a	8.80	b
Phosphate absorption coefficient	-	1770	a	750	b
Exchangeable Ca	$cmol_c$ kg^{-1}	9.1	a	4.68	b
Water soluble Ca	$cmol_c$ kg^{-1}	0.443	a	0.334	b
Soil available N[a]	mg kg^{-1}	33.9	b	47.3	a
Soil available phosphate	mg P_2O_5 kg^{-1}	230	b	409	a
Exchangeable K	$cmol_c$ kg^{-1}	0.687	a	0.729	a
Stem number per plant					
Andover (total plants sampled = 559)	stems per plant	1.9	b	2.20	a
Toyoshiro (total plants sampled = 804)	stems per plant	3.5	a	3.40	a
Kitahime (total plants sampled = 634)	stems per plant	2.9	b	3.30	a
Snowden (total plants sampled = 758)	stems per plant	3.4	b	3.80	a

[a]Soil available N; hot water extracted N. For soil properties, paired mean comparisons were made using t-test with n = 90 for Tokachi and n = 80 for Kamikawa district. Soil/plant property with different letters within a row indicate statistically significant (*$p < 0.05$*).

Furthermore, Tokachi district had over two times the PAC than Kamikawa soils. Also, the Al_o contents in Tokachi fields were approximately six-fold higher as compared to Kamikawa fields.

Table 3.3. Characteristics of tuber yields and yield components among the four processing potato cultivars grown in fields of Tokachi and Kamikawa districts.

Cultivar	Number of sites	Stem number (per plant)	Tuber number (per plant)	Mean tuber weight (g)	Tuber yield (Mg ha^{-1})	Specific gravity
All dataset						
Andover	30	2.1 ± 0.27 c	7.2 ± 1.5 c	113 ± 21 a	37 ± 9.6 b	1.079 ± 0.010 c
Toyoshiro	50	3.4 ± 0.63 a	11 ± 1.8 a	92 ± 12 b	45 ± 5.7 a	1.088 ± 0.010 a
Kitahime	40	3.0 ± 0.58 b	8.4 ± 1.5 b	114 ± 21 a	42 ± 7.1 a	1.086 ± 0.010 ab
Snowden	50	3.5 ± 0.69 a	10 ± 1.7 a	99 ± 14 b	45 ± 6.7 a	1.083 ± 0.010 b
Tokachi						
Andover	10	1.9 ± 0.28 c	7.1 ± 1.3 b	119 ± 21 a	41 ± 6.4 ab	1.080 ± 0.002 b
Toyoshiro	30	3.5 ± 0.54 a	11 ± 1.6 a	90 ± 11 b	46 ± 5.7 a	1.089 ± 0.006 a
Kitahime	20	2.9 ± 0.58 b	8.6 ± 1.7 b	109 ± 17 a	41 ± 7.0 b	1.085 ± 0.007 a
Snowden	30	3.4 ± 0.65 a	10 ± 1.7 a	97 ± 13 b	43 ± 6.0 ab	1.081 ± 0.050 b
Kamikawa						
Andover	20	2.2 ± 0.24 c	7.2 ± 1.7 b	109 ± 21 ab	35 ± 11 b	1.078 ± 0.006 b
Toyoshiro	20	3.3 ± 0.74 b	10 ± 1.8 a	96 ± 14 b	44 ± 5.8 a	1.087 ± 0.007 a
Kitahime	20	3.2 ± 0.54 bc	8.3 ± 1.3 ab	120 ± 23 a	43 ± 6.9 a	1.087 ± 0.005 a
Snowden	20	3.8 ± 0.67 a	10 ± 1.7 a	102 ± 16 b	46 ± 7.7 a	1.086 ± 0.005 a

Within location, means in the same column followed by different letters are significantly different ($p < 0.05$, Tukey HSD test)

Using both Japanese (Cultivated Soil Classification Committee 1995) and USDA soil classification system (Soil survey Staff 2014), we found that 78 out of 90 fields in Tokachi were classified as Andisols and the rest as Entisols (Table 3.2). Seventy-two out of 80 fields in Kamikawa were classified as Inceptisols and the remainder was Entisols. Phosphate absorption coefficient (PAC) is a conventional Japanese method used to determine the degree of soils' capacity to retain phosphate. Eighty-six percent of Tokachi soils had PAC values greater than 1500, the threshold criteria used to separate Andisols from other types of soils in Japan (Cultivated Soil Classification Committee 1995). Exchangeable Ca was higher in Tokachi compared to Kamikawa district. Although total N was higher in Tokachi soils, the available N was higher in Kamikawa soils. Similarly, soil available P and K were higher in Kamikawa soils as compared to Tokachi soils (Table 3.2).

3.4.2. Cultivar differences in yield components

Considerable cultivar variation in yield components was found among the four cultivars across both districts and growing seasons. Stem numbers per plant averaged across cultivars were 2.1, 3.4, 3.0, and 3.5 for Andover, Toyoshiro, Kitahime, and Snowden, respectively (Table 3.3). The trend of stem numbers per plant indicated that Toyoshiro and Snowden had the highest values, and this was consistent in both districts. Andover cultivar, which is an early maturing cultivar consistently showed low stem number per plant in both districts. Stem number is reported to be much influenced by factors such as cultivar (Lynch and Tai 1989), physiological age of seed tuber (Iritani 1968), calcium content in potato seed piece (Dyson and Digby 1975; Busse et al. 2008), and size of potato seed (Harris 1992). After planting, stems emerge from growing points (eyes) on the seed piece. Cultivars with genetically higher number of growing points per seed tuber tend to sprout much more profusely leading to many stems per plant.

Nielson et al. (1989) observed Russet Burbank having two times higher number of eyes compared to similar size seed tuber of Nooksack that consequently resulted in development of more stems.

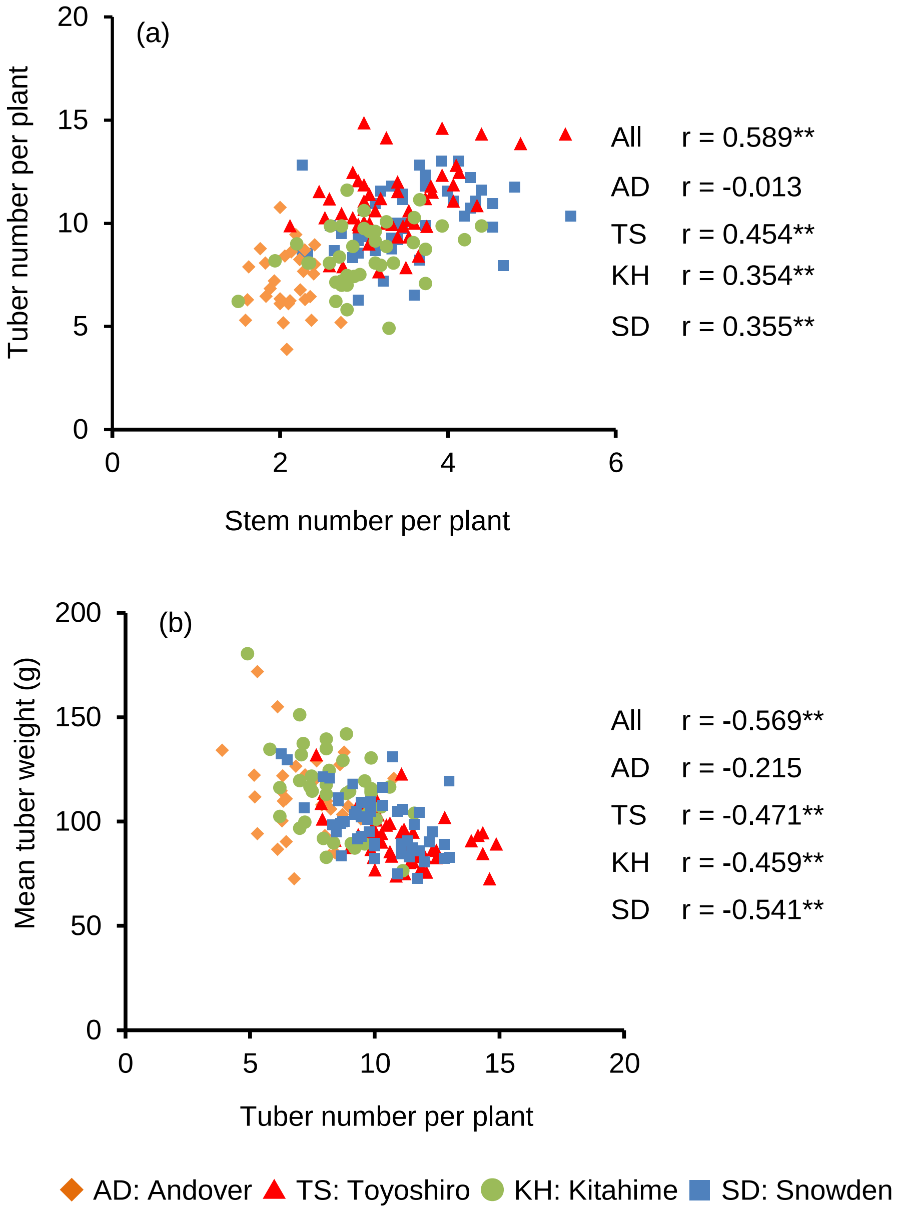


Figure 3.1. Scatter plot of the relationships between (a) number of tubers per plant and number of main stems per plant, and (b) average tuber weight and number of tubers per plant over two seasons for all the four cultivars combined (n = 170) and separated. r = Pearson correlation coefficient, asterisks indicate significant relationships between variables at $p < 0.01$ (**).

These results demonstrate an inherent physiological difference in sprouting characteristics among the four cultivars. The analysis of variance revealed that growing season by soil type interaction as well as cultivar were significant ($p < 0.05$) sources of variation for stem numbers per plant (Table 3.4). The interactive effects resulted from the differences in stem numbers observed between the two growing seasons. Stem numbers were greater in the Kamikawa district where availability of N, P, and K were greater but exchangeable and water soluble were lower than the Tokachi district (Table 3.2). Higher stem numbers were observed in 2013 compared to 2014 (data not shown). This could be related to differences in physiological age of seed tubers used that caused differences in sprouting characteristics. Late planting of tubers in 2013 growing season in Kamikawa district increased the physiological age of seed tubers. Advanced seed-tuber age accelerates plant emergence, establishment, and decreases the dominance of apical growing point tubers that result in increased number of stems (Knowles and Knowles 2006).

The pattern of number of tubers per plant was similar to that of stem number per plant. The rank of cultivars in decreasing order of tuber number per plant was Toyoshiro (11 tubers), Snowden (10 tubers), Kitahime (8.4 tubers), and Andover (7.2 tubers; Table 3.3). It was evident from the results that cultivars with high stem number per plant also showed higher number of tubers per plant. This was further confirmed by the correlation analysis that showed a significant relationship ($p \leq 0.001$) between stem numbers per plant and tuber number per plant (Fig. 3.1a). The results suggest that cultivars with more stems produce more tubers per plant. However, when data were separated based on cultivar, differential response of tuber number to stem number was observed especially for Andover that indicates the result is not universal to all cultivars. Thompson and Taylor (1974) found that the maximum number of tubers attained by Pentland Marble cultivar was 1.4 times higher than Maris Peer cultivar at the same stem density. They suggested that the difference was caused by differences in genetic potential for production that made cultivars attain different number of tubers per stem. Stems of Andover did not vary much compared to other cultivars reflecting a genetically fixed number of stems. Previous studies have shown that cultivars with long dormant period tend to have few sprout growth (Bornman and Hammes 1977). Andover has a dormant period of about two weeks longer than Atlantic and three weeks longer than Superior (Plaisted et al. 1998). The main sources of variation in tuber number per plant were interaction effects of cultivar by growing season as well as growing season by soil type (Table 4). Tubers per plant were higher in 2013 than 2014 growing season due to more stem numbers. Stems are independent production units, with increase in stem numbers more tubers are produced (Moorby 1978). Surprisingly, when tuber number per plant were separated based on soil type, the difference between two locations was not significant despite Kamikawa having significantly higher stem number per plant (Table 3.2; Table 3.4). The reason for these contrasting effects is not clear, in part this could be because tubers less than 20 g were not harvested that might have affected the results of tuber number per plant. Additionally, past studies have demonstrated the role of N nutrition in inhibiting tuberization in potatoes (Krauss 1985). Soil available N was significantly higher in Kamikawa compared to Tokachi district (Table 3.2).

The mean tuber weights were 113, 92, 114, and 99 g for Andover, Toyoshiro, Kitahime, and Snowden, respectively (Table 3.3). Of the four cultivars, Andover and Kitahime showed significantly bigger sized tubers compared to others. In agreement with most studies, mean tuber weight was negatively related to number of tubers per plant (Fig. 3.1b). This suggests that stem number influences tuber size distribution from predominantly larger tubers at low stem density to predominantly small tubers at high stem density. Decrease in mean tuber weight at high stem and tuber density is caused by inter-tuber or inter-stem competition for available resources of light, water and nutrients (Moorby 1967; Thompson and Taylor 1974). Toyoshiro and Snowden have more stems per plant that resulted in more tuber set per plant and lower mean tuber weight. Tuber size distribution is an important factor in determining growers' profits. Potatoes intended for processing have size specifications, and growers often get bonus based on the percentage of yield made up of tubers within desired size grades (Rex 1990). Specific size category is demanded by processing industry because it facilitates the mechanical removal of the peels more efficiently and with minimum loss. In contrast, wide variation in size requires size grading at the factory and some cases cutting the large ones for efficiency in processing (Gould 1999). To optimize tuber sizes desirable for processing products, growers need to regulate stem numbers since more stems result in smaller tuber sizes.

Table 3.4. Significance of growing season, soil type, and cultivar effects on various yield components, tuber yields, and specific gravity of the four processing cultivars grown in Tokachi and Kamikawa districts in 2013 and 2014 growing seasons.

	Stem number per plant	Tuber number per plant	Mean tuber weight	Tuber yield	Specific gravity
P-values					
Growing season x soil type x cultivar	0.687	0.074	0.720	0.119	0.624
Soil type x cultivar	0.111	0.554	0.244	**0.022**	**0.037**
Growing season x cultivar	0.279	**0.021**	0.113	**0.016**	0.370
Growing season x soil type	**0.015**	**0.014**	**0.003**	0.403	0.827
Cultivar	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Soil type	**0.036**	0.174	0.241	0.494	0.403
Growing season	**0.039**	0.454	0.257	**0.004**	0.487

Values of P in bold are significant ($p < 0.05$).

Significant growing season and soil type effects were observed on mean tuber weight (Table 3.4). This could be related to differences in stem numbers between the two growing seasons that influenced number of tubers produced and tuber size distribution. Past studies have reported the influence of Ca in reducing tuber number per plant and increasing size of tubers (Ozgen and Palta 2005). Conversely, other studies have reported that high availability of P increases tuber number per plant that was associated with increase in undersized tubers (Rosen and Bierman 2008). In the current, Soil exchangeable Ca was lower than the recommendation in both districts although Tokachi had significantly higher soil exchangeable Ca compared to Tokachi district (Table 3.2). On the other hand majority of the soils in both districts had available P higher than the recommendation. The roles of Ca and P in regulating tuber size might have been confounded by the fact that they can form insoluble compounds calcium phosphate minerals in the soil (Tisdale and Nelson 1975) which rendered particularly Ca less available to plant available.

3.4.3. Among and within cultivar differences in tuber yields

Averaged tuber yields across districts were 37, 45, 42, and 45 Mg ha^{-1}, for Andover, Toyoshiro, Kitahime, and Snowden, respectively (Table 3.3). De la Morena et al. (1994) attributed variation in tuber yields among potato cultivars to differences in their yield components. Physiologically, tuber yield is a function of number of stems per plant, number of tubers per plant, and mean tuber weight (Lynch and Tai 1989). The multiplicative product of the three yield components forms total tuber yields. Although stem number per plant is one of the most important yield components in potato production, the current study shows no significant relationships between stem density and both total and marketable tuber yields (Fig. 3.2). This observation supports the findings of Hammes (1985) who reported lack of yield response to different stem densities. However, Goodwin et al. (1969) and Sekhon and Singh (1985) measured a decrease in yield as stem density increased while De la Morena et al. (1994) and Bussan et al. (2007) found an increase. The disparities in yield response to stem densities among previous studies can be attributed to differences in cultivars and statistical models used. For example, Del la Morena et al. (1994) and Bussan et al. (2007) used path analysis and nonlinear regression model, respectively.

It was evident from the data that both total and marketable yields were significantly influenced by tuber density (Fig. 3.3a and 3.3b). Although Hames (1985) did not find a corresponding increase in yield with increase in tuber density, Bussan et al. (2007) and De la Morena et al. (1994) found an increase.

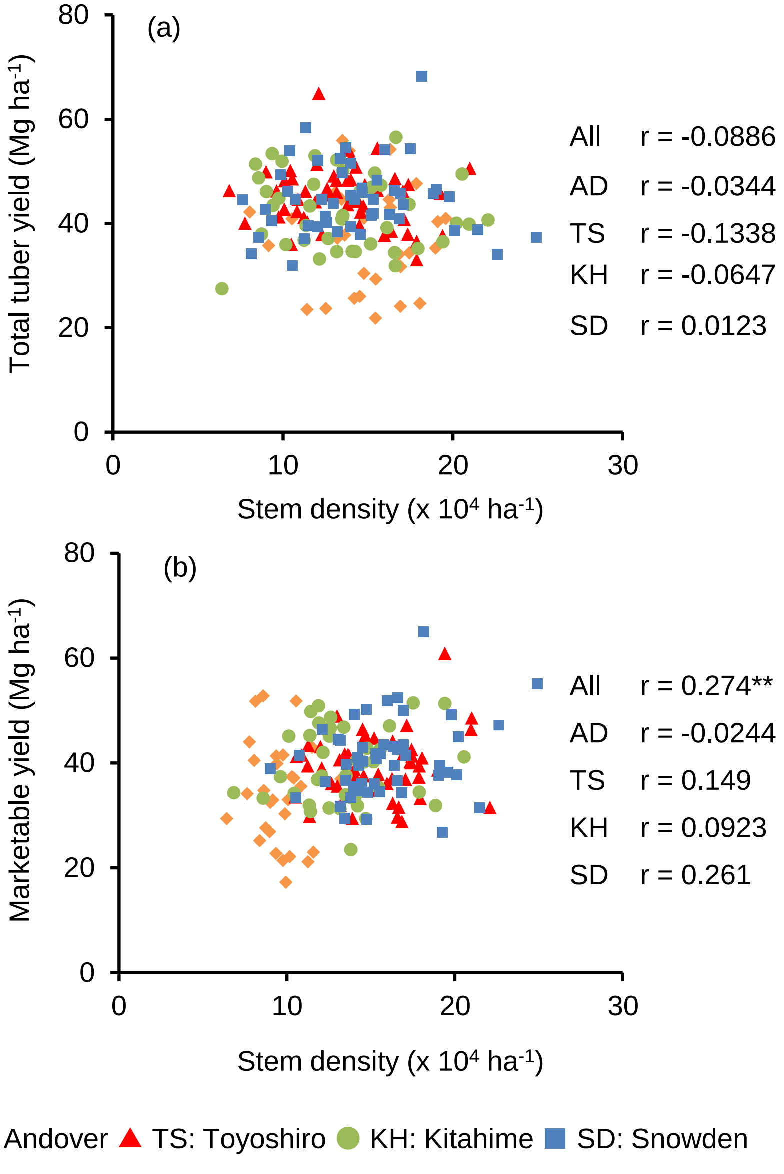


Figure 3.2. Scatter plot of the relationships between (a) total tuber yield and stem density, and (b) marketable yield and stem density over two seasons for all the four cultivars combined (n = 170) and separated. r = Pearson correlation coefficient, ** indicate significant relationships between variables at $p < 0.01$.

On plant basis, Lynch et al. (2001) suggested that tuber number per plant may be an important early season predictor of tuber yield while Lemaga and Caesar (1990) reported tuber number and stem number per plant to be better determinants of tuber yields than mean tuber weight. The observed high yields in Toyoshiro and Snowden cultivars could be related to its significantly high tuber number per plant and high tuber densities.

Although Andover and Kitahime cultivars had large sized tubers, they yielded very low because of low tuber number (Table 3.3). Zelalem et al. (2009) demonstrated the importance of both mean tuber weight and total tuber number in improving tuber yield.

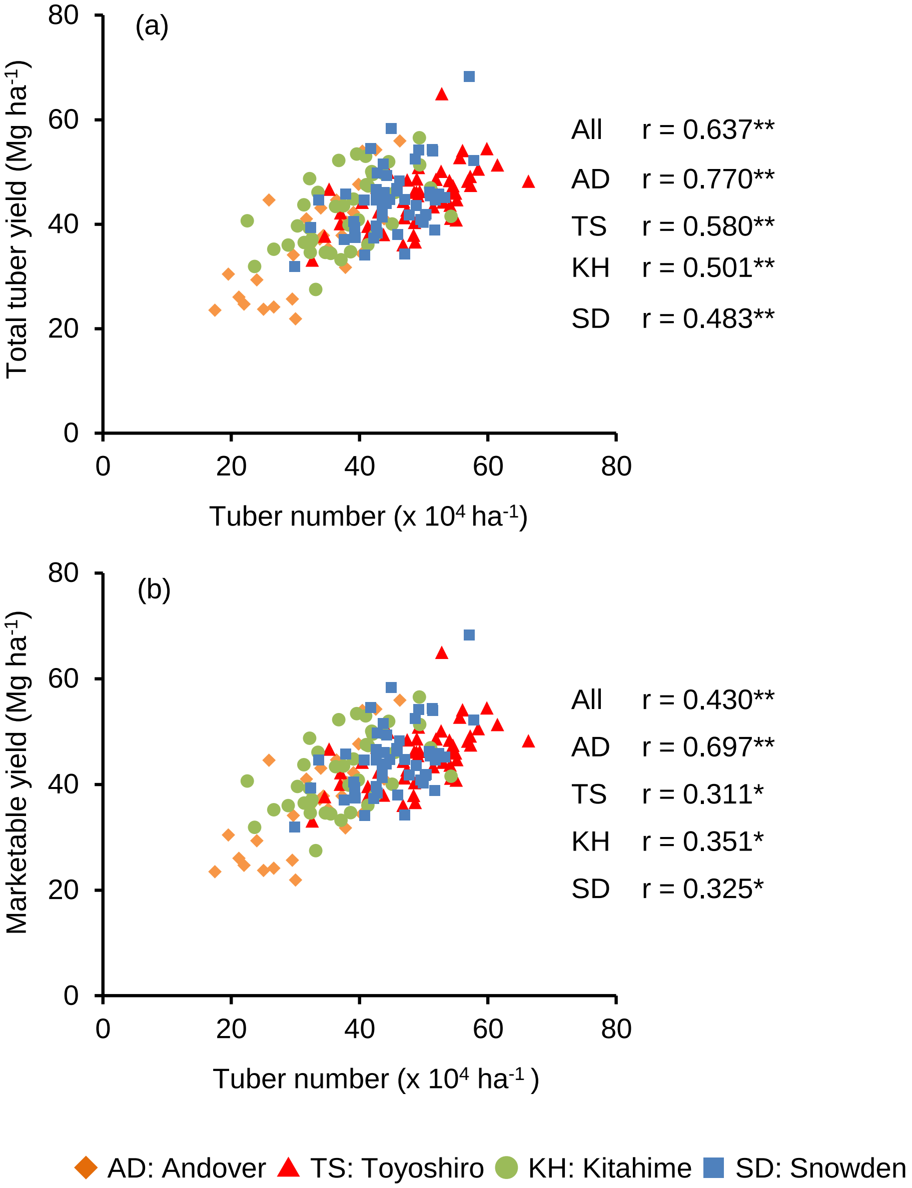


Figure 3.3. Scatter plot of the relationships between (a) total tuber yield and tuber number per ha, and (b) marketable yield and tuber number per ha over two seasons for all the four cultivars combined (n = 170) and separated. r = Pearson correlation coefficient, *, ** indicate significant relationships between variables at $p < 0.05$ and $p < 0.01$, respectively.

Moreover, total biomass production of potato cultivars depends on the absorbed photosynthetically active radiation and its conversion efficiency to dry matter (Oliveira et al. 2016). Andover is an early maturing cultivar and has less period of photosynthesis and translocation of assimilates to tubers and hence low yield. Late planting of potatoes in 2013 in Kamikawa district also affected the yield of Andover. Since Hokkaido region has a short growing season, early maturing cultivars such as Andover are preferred to be grown as they allow growers to prepare for the next crop such as winter wheat. Furthermore, earlier production enables potato processing factories to open their season earlier and get a better use of their capital investment.

Finally, results of analysis of variance revealed that tuber yields were influenced by the interaction effects of growing season and soil type (Table 3.4). Tuber yields were lower in 2013 than 2014 growing season (data not shown) because of bad weather conditions observed in Kamikawa district that significantly caused reduction in tuber yields especially Andover. This resulted in cultivar by growing season interaction in tuber yield. Additionally, spatial distribution of precipitation in 2014 growing season was well synchronized with potato growth stages that may have contributed to high tuber yields (Table 3.2). On soil type basis, tuber yield was higher in Tokachi than Kamikawa district because tuber density was 10% higher in Tokachi, hence the interaction effects between soil type (Table 3.3). Low temperatures early in the season delays canopy development, and reduce time available for tuber growth particularly in climate with short growing season (Yuan and Bland 2005). Low temperature and sunlight hours in the spring of 2013 in Kamikawa district delayed planting and thus may have contributed to reduction in tuber yields that caused interaction effects between growing seasons.

Potato tuber yields data were further summarized using box plots to allow comparison within and among cultivar variation (Fig. 4.4a and 4.4b). Results showed high variation in yield both within and among cultivars that is common in growers' fields due to differences in agronomic practices. The variation reflects both cultivar differences in yield potential and field to field differences due to soil management. Kamikawa district had large variation in tuber yields compared to Tokachi because of topography. The landscape of Kamikawa district is hilly and potato fields are located in lowlands and highlands that may have created microclimates that contributed to localized differences in yields.

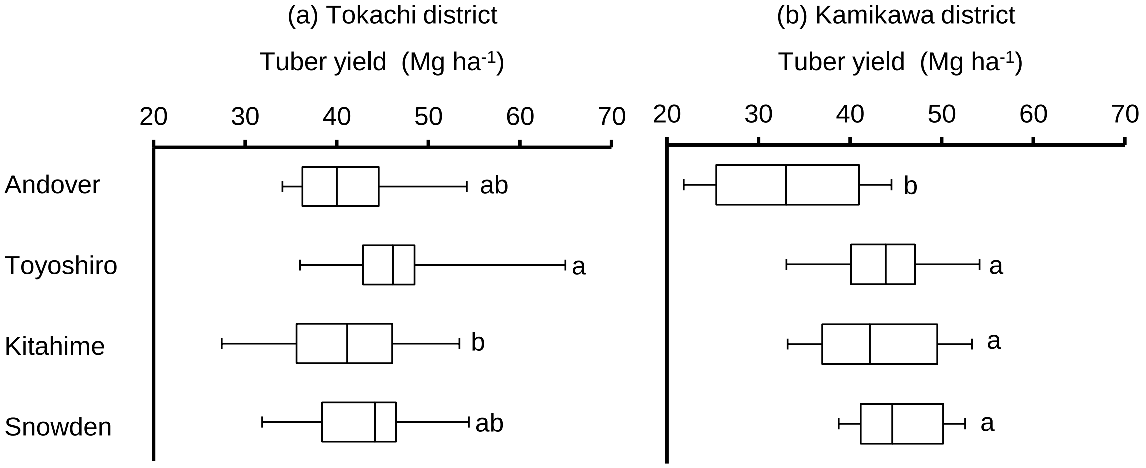


Figure 3.4. Box plots describing potato tuber yield variation among the four potato processing cultivars surveyed in Tokachi and Kamikawa districts. The central horizontal line in the box marks the median of the samples, the box edges represent first and third quartile. The whiskers show the range of observed values that are not within the first and third quartile.

In addition to topography, differences in management practices create zones of low yielding and high yielding areas (Rowe et al. 2006). In this context, our previous study (Gondwe et al. 2017), found an on-going excessive phosphate fertilizer application in the studied fields, and yields were not affected by phosphate fertilizer application. Soils also contain exceptionally high levels of available phosphate which may predispose tubers to high phosphorus content.

We also observed irregular intra-row spacing in the range of 19 to 42 cm apart (data not shown) while the regular intra-row spacing for potato in Hokkaido region is 30 cm. Love and Thompson-Johns (1999) found that plant spacing lead to a change in tuber size distribution from predominance of larger tubers at wide spacing to predominance of small tubers at narrow spacing. Moreover, in-row spacing of plants affects both plant and stem density. Studies have also shown that stem density is related to tuber density (Bussan et al. 2007), and the observed field to field differences in stem densities may have contributed to variation in both yield components and subsequently tuber yields.

3.4.4. Effects of cultivar type on quality of tubers

Specific gravity for Andover, Toyoshiro, Kitahime, and Snowden were 1.079, 1.088, 1.086, and 1.083, respectively (Table 3.3). Sato et al. (2017) documented specific gravity between 1.065 and 1.110 for Toyoshiro, 1.060 and 1.105 for Kitahime and 1.070 and 1.100 for Snowden sourced from the same districts. The results of specific gravity reported in our study were within the ranges reported by previous study. According to Mosley and Chase (1993), specific gravity values between 1.060 and 1.069 are regarded as low, while values between 1.070 and 1.079 are medium and 1.080 to 1.089 are regarded as high. High specific gravity tubers are required for chips as they result in a greater product yield per unit fresh mass. Among the four cultivars, Andover, an early maturing cultivar had the lowest specific gravity (Table 3.3) but within the required range for processing. This finding supports Belanger et al. (2002) who reported low specific gravity in early maturing cultivars compared to late maturing cultivars. Long duration cultivars intercept more solar radiation that is converted into carbohydrates that is partitions to the tubers. Early maturing cultivars such as Andover have shorter leaf longevity that shortens the period to intercept and conversion of photosynthetically active radiation into carbohydrates, hence low specific gravity.

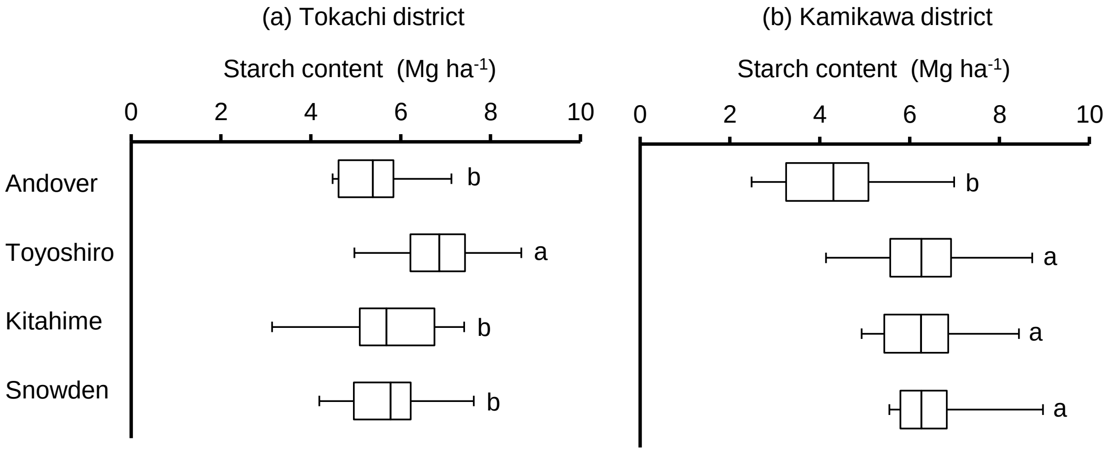


Figure. 3.5. Box plots of the calculated starch content for the four potato processing cultivars surveyed in Tokachi and Kamikawa district. The central horizontal line in the box marks the median of the samples, the box edges represent first and third quartile. The whiskers show the range of observed values that are not within the first and third quartile. Different letters indicate significance difference, same letter indicates no significant difference at p <0.05 by Tukey HSD test.

In addition, late planting of potatoes in Kamikawa district in 2013 growing season affected the performance of Andover more than the mid-season maturing cultivars. Specific gravity is not only a cultivar characteristic, but is also influenced by factors such as soil type, fertilization, and water supply during the growing season (Steyn et al. 2009). In the current study, analysis of variance showed that soil type and cultivar were the significant sources of variation for specific gravity (Table 3.4). Individual cultivars performed differently across the two districts that led to genotype by soil type interaction in specific gravity (Table 3.4). For example, the performance of Snowden was significantly low in Tokachi district compared to other mid-season cultivars (Toyoshiro and Kitahime). This was not expected because Snowden is an internationally known cultivar for having high specific gravity when grown in the environments where it was developed (Hutchinson et al. 2003). We suspect that the poor performance of this cultivar in Tokachi district may suggest that the cultivar does not perform well in soil types found in this area.

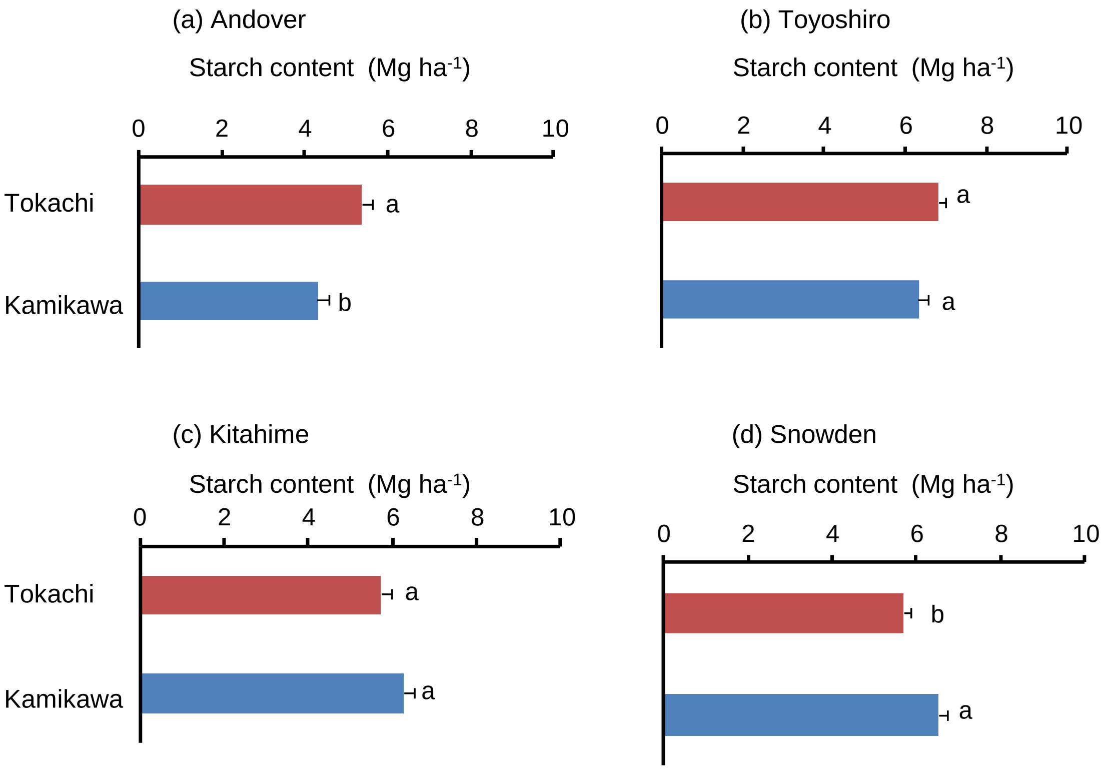


Figure 3.6. Starch content of (a) Andover, (b) Toyoshiro, (c) Kitahime and (d) Snowden separated based on soil types. Different letters indicate T-test significant difference at p <0.05.

Tokachi soils have high soil organic matter (SOM) content as indicated in soil total carbon content (Table 3.1), that may have led to high soil nitrogen (N) supply to crops through organic N mineralization. Supply of more than optimal N to tubers particularly during late potato bulking period, stimulates vegetative growth and reduces available dry matter for tubers (Laboski and Kelling 2007). The goal of breeders is to produce cultivars that perform well in a wide range of environments because growers and processors require reliable production and quality of potato (Affleck et al. 2008). This information is therefore, important to breeders, physiologists and agronomists who are interested in improving performance of potato crop across different environments. The good performance of Toyoshiro in terms of high specific gravity across the two districts explains the reasons that contribute to the continuing popularity of this cultivar in Japan. This information is also very important to growers to carefully select cultivars adapted to a given locality to maximize both yield and quality. Starch is the main component of carbohydrate in potato tubers. To understand the amount of carbohydrates contained in tubers, starch content was used as a proxy value for carbohydrate. The highest and lowest starch production was observed in Toyoshiro and Andover cultivars, respectively. (Fig. 3.5a and 3.5b). Starch production is associated with length of growing season, and late maturing cultivars tend to accumulate more starch than early maturing cultivars (Lisinska and Leszczynski 1989). Surprisingly, separation of individual cultivar starch content found that locally produced cultivars were less affected by the influence of soil type compared to imported cultivars (Fig. 3.6). Starch yield for Andover was significantly higher in Tokachi compared to Kamikawa district whilst the performance Snowden cultivar was vice versa. Low starch production in Andover, therefore, was expected since it is an early season cultivar. Although Snowden cultivar is very popular in USA for its good processing quality, its use in Hokkaido region is somehow limited because of its longer growing period. The region has short growing season, and in the crop rotation, potato precedes winter wheat that is planted in the autumn (from mid-September to late October). Late maturing potato cultivars such as Snowden are less preferred by growers because its inclusion in the rotation does not provide growers enough time window for seeding of winter wheat.

3.5. Summary

The study has confirmed that potato processing cultivars have different yield components that reflect their inherent physiological differences. Yield components and yield were also influenced by soil types. Stem number per plant determined number of tubers to be produced that in turn affected the size of potato tubers. Moreover, stem density was not related to either total or marketable yield. Growers can optimize marketable yield and crop value by regulating number of stems per plant. This can be achieved by using more juvenile potato seed tubers that produce less stems. Our results show that in general, in Kamikawa district there were more stems produced as compared to Tokachi district. Interestingly, the Kamikawa soils had more available N, P, and K and less exchangeable Ca. Use of potato seed tubers with high calcium is necessary for growth of the apical meristem of the sprouting stems that prevents loss of apical dominance. For some cultivars starch yield was also affected by soil type, growers need carefully select cultivars adapted to a given locality to maximize marketable yield and processing quality. This information is very important to growers to carefully select cultivars adapted to a given locality to maximize both tuber yield and quality.

CHAPTER 4. INFLUENCE OF AVAILABLE SOIL NUTRIENTS AND IN-SEASON NPK APPLICATION ON YIELD, QUALITY AND NUTRIENT COMPOSITION OF POTATO TUBERS

4.1. Abstract

Proper management of N, P and K fertilizers is considered very important for maximizing tuber yield and attain desirable processing quality. Generally, farmers apply NPK fertilizer rates based on the preplant soil tests. However, very limited information is available on the influence of available soil nutrients and in-season NPK application rates on yield and quality of tubers. In present study, paired soil and tuber samples were evaluated from 170 commercial production sites to evaluate potential relationship between soil nutrients, tuber yield, and tuber quality. We found that about 50%, 80%, and 70% of farmers applied more N, P, and K than the recommended rates, respectively. Results of our study suggest that, in general soil available N, P, and K increases tuber N, P, and K concentrations and tuber N and K concentrations can reduce specific gravity. Interestingly, tuber P concentration had no effect on specific gravity. We also found some variations in their responses among the cultivars suggesting some genetic control for the traits studied. Our results also suggest that application of N, P, and K fertilizers in excess of recommended rates on soils that are already rich in these nutrients does not increase tuber yields. Our results suggest that farmers need to apply fertilizers based on recommendation to reduce potential environmental degradation associated with excessive fertilization.

Key words: Soil available nutrients, In-season fertilization, Tuber yield, Specific gravity

4.2. Introduction

Global consumer demand for potatoes continue to change from fresh potatoes to value added processed food products such as chips (Scott and Zelada 2011; Wang et al. 2012). In Japan, the demand for processed potatoes exceeds the domestic supply (Mori et al. 2015), hence there is need to increase production of processing potato yields to meet the consumer demand. Hokkaido, northernmost region of Japan, is the major producer of potato in the country accounting for over 80% of the nation`s production (MAFF 2016). The region has cool temperatures and large-scale agricultural land that provide suitable conditions for potato production. Twenty-four percent of potatoes produced in Japan are used in processing industry (GAIN 2014), and recent research has shown a gradual shift in production from starch cultivars to processing cultivars to cope with the demand (Deguchi et al. 2016). While increasing potato yield is important to meet the current demand, processing industry has strict market requirements for tuber size and quality. Proper fertilizer management is a necessary agronomic practice to achieve these goals in potato production (Laboski and Kelling 2007; Rosen and Bierman 2008).

Since the start of green revolutions in 1950s, the uses of chemical fertilizers have been widely practiced in agricultural production to increase crop productivity (van der Bon et al. 2017). This is particularly common in potato production (Errebhi et al. 1998; Huchmuth et al. 2002) due to its low nutrient efficiency and naturally shallow and poor developed root system (Iwama 2008; Sharma et al. 2017). In addition, the general belief that potatoes show large response to NPK fertilizer rates justifies large inputs even on soils with large amounts of available N, P, and K nutrients (Hopkins et al. 2010; Maltas et al. 2018). This practice may have a profound effect on yield and quality of processing tubers. For example, excessive N fertilizer is known to promote vegetative growth that can delay tuber set, reduce tuberization leading to reduced yield (Abdalla et al. 1995; Vos 1997). In addition, excess N reduces the quality of processing tubers through reduction in dry matter content (Vreugdenhil and Sergeeva 1999) and increases asparagine in potato tubers that can cause acrylamide compound in potato chip products (Rosen et al. 2018).

Similarly, excess P application has been found to increase tuber set and reduce tuber size that reduces marketable yields (Sommerfeld and Knutson 1965; Rosen and Bierman 2008). Moreover, excessive P application can lead to P accumulation in the soil that poses high risk of water quality degradation through overflow and soil erosion (Ruark et al 2014). Conflicting results of excess K application on quality and yield have been reported. Allison et al. (2001b) and Kang et al. (2014) found a decrease in potato yield and tuber specific gravity with increasing levels of K fertilizer, while AbdelGadir et al. (2003) did not observe any change. Other studies observed that K in the form of KCl lowered specific gravity more than K_2SO_4 (Kumar et al. 2007; Westermann et al. 1994).

Specific gravity is an important potato tuber quality parameter related to dry matter content. It is the widely accepted measure by processing industry to assess suitability of tubers for processing (Kleinkopf et al. 1987). Tubers with high specific gravity have greater product yield per unit fresh weight than tubers with low dry matter content (Burton et al. 1992). In addition, tubers with high specific gravity require less energy input during frying or dehydration to remove water and generally produce products with better texture (Mosley and Chase 1993). For potato processing, specific gravity ranges from 1.080 to 1.089 are desired for high quality potato chip products (Sun et al. 2017).

Although Hokkaido Fertilizer Recommendation have established the standard N, P, and K fertilizer rates for potatoes (Department of Agriculture, Hokkaido Government 2015), recent reports have raised some severe concerns about potential impacts of phosphate fertilization practices in potato cultivated fields (Tani et al. 2010; Tani et al. 2011). Additionally, no conventional study has been undertaken in commercial fields to establish the relationships between tuber N, P, K concentrations and soil available N, P, and K. In our study, we obtained paired soil and tuber samples from the same 170 separate commercial production sites. These paired samples gave us the opportunity to not only study yield response to fertilizer rates but also study the relationships between soil nutrient availability and tuber nutrient concentrations.

The objectives of this study were to i) evaluate potato tuber yield response to soil available N, P, and K and in season N, P, and K fertilization, (ii) determine the influence of soil available N and

P as well as exchangeable K on tuber N, P and K concentration iii) assess the effects of soil available N and as well as exchangeable K on tuber specific gravity.

4.3. Materials and methods

4.3.1. Study sites

The study was done in the two major potato production districts, Tokachi and Kamikawa in Hokkaido prefecture, northern Japan, during 2013 and 2014 growing seasons. Almost 50% of the total potato production in Hokkaido comes from these two districts (MAFF 2016). The regions have contrasting soil types, Tokachi district is dominated by volcanic ash derived soils known as Andisols that account for 57% of the total production area (Cultivated Soil Classification Committee 1995; Hashimoto 2008) whilst Kamikawa district is dominated by soils of pyroclastic flow deposit origin classified as Inceptisols (Soil Survey Staff 2014). Soil and potato tubers samples were collected from 90 and 80 fields in Tokachi and Kamikawa districts, respectively (Chapter two, Fig. 2.1).

4.3.2. Soil and potato tuber yield sampling

On each of the selected study field, sampling plot of 5-m row length was established where plant stand was relatively uniform (no missing plant) and represented the commercial field. The size of each selected plot was three rows wide and 15 plants long, with a 75 cm row interval and 30 cm plant interval. The sampling plot was placed at least 3 m away from the edge of the field and tractor paths to avoid border effects. Areas close to the ditches and manure dumps were avoided. As a result of the crop-rotation sequences, different commercial fields were used each year. Potatoes were preceded by soybean and sugar beet in Tokachi district, and sugar beet and winter wheat in Kamikawa district.

Soil samples were collected at flowering stage from two side rows. Ten sub-samples (5 samples from each row) were collected from 0-to-20 cm depth between plants. All the collected soil samples from a given site were thoroughly mixed and composited into one single soil sample for analysis.

Potato tubers were excavated by spade and collected by hand from all 15 plants in the center row, and tuber greater than 20 g were weighed to obtain yield per plot. Potato tuber specific gravity was determined by the hydrometer method on a 3-kg subsample of the marketable potatoes per field (Edgar 1951). Cultivars included Andover (n = 30), Toyoshiro (n = 50), Kitahime (n = 40), and Snowden (n = 50).

4.3.3. Soil and potato tuber analyses

Soil samples were air dried and passed through a 2-mm sieve before chemical analysis. Total carbon (TC) and total nitrogen (TN) contents using a dry combustion method with a Vario EL III analyzer (Elementar Analysensysteme, Hanau, Germany). Acid-oxalate extractable aluminum (Alo) was determined using a 0.2-mol L^{-1} acid ammonium oxalate solution (pH 3) at a soil/solution ratio of 1:100 for 4 h equilibration in the dark (Blakemore et al. 1987), followed by measurement using the ICP-ES (ICPS-8100, Shimadzu Corporation, Kyoto, Japan). The cation exchange capacity (CEC) was measured by using ammonium acetate extraction method buffered at pH 7 as described by Schollenberger and Dreibelbis (1930). The K concentration in the ammonium acetate extract was quantified by atomic absorption spectrophotometer (AAS; Z-5010, Hitachi Corporation, Tokyo, Japan). The soil K that is immediately available for uptake by plants is usually described as exchangeable. In this chapter, the terms available and exchangeable will be regarded as synonymous. Phosphate absorption coefficient (PAC) was estimated based on the phosphate retained by the soil after equilibrium using a 2.5% diammonium phosphate solution, and measured by the colorimetric molybdate yellow method (Nanzyo 1997). PAC values determined by this procedure have been used extensively in Japan as an index of soil`s capacity to make phosphate unavailable to crop. Available N was determined by hot water extraction method because it is the recommended method for routine evaluation for making N fertilizer recommendation in Hokkaido (Department of Agriculture, Hokkaido Government, 2015). For this analysis, N was measured by heating 1:10 soil/water solution in an autoclave at 105°C for one hour (Cutin et al. 2006), and N was quantified by total organic carbon analyzer (TOC-VCPH TNM-1, Shimadzu Corporation, Kyoto, Japan). Soil-available phosphate was estimated using the Truog method (Truog 1930). For this analysis, 0.5 mmol L^{-1} sulfuric acid (H_2SO_4) and ammonium sulfate ($(NH4)_2SO_4$) at pH 3 were used. The phosphate concentration in the filtrate was quantified by the colorimetric molybdate blue method developed by Murphy and Riley (1962).

Tuber N concentration was assessed on ground samples and the measurement was undertaken using a dry combustion method with a Vario EL III analyzer (Elementar Analysensysteme, Hanau, Germany; Nagy 2000). Whilst tuber P and K were determined by digesting ground potato samples in acid (H_2SO_4/H_2O_2) by Kjeldahl method (Kjeldahl 1883), and quantified using the ICP-ES (ICPS-8100, Shimadzu Corporation, Kyoto, Japan).

4.3.4. Statistical analyses

Statistical analyses were carried out using Excel Statistics 2012 (Social Survey Research Information, Tokyo, Japan). Descriptive statistics for the measured soil properties were calculated. Pearson correlations were performed to determine the extent of relationships among soil available nutrients, tuber N, P, and K concentration.

4.4. Results and discussion

4.4.1. Soil characteristics of the fields

Inherent characteristics (TC, CEC, PAC and Al_o) of soils from Tokachi and Kamikawa districts were distinctly different (Table 4.1). Soils in the Tokachi district were more than twofold higher in organic matter (TC) and CEC as compared to Kamikawa district. Furthermore, Tokachi district had over two times the PAC than Kamikawa soils. Also, the Al_o contents in Tokachi fields were approximately six-fold higher as compared to Kamikawa fields. Using both Japanese (Cultivated Soil Classification Committee 1995) and USDA soil classification system (Soil Survey Staff 2014), we found that 78 out of 90 fields in Tokachi were classified as Andisols and the rest as Entisols (Table 4.2). Seventy-two out of 80 fields in Kamikawa were classified as Inceptisols and the remainder was Entisols.

Table 4.1. Descriptive statistics of the measured soil properties in Tokachi and Kamikawa district.

Soil property	Unit	Tokachi (n = 90)						Kamikawa (n = 80)					
		Mean		SD[c]	Range			Mean		SD	Range		
Total carbon	g kg^{-1}	49.8	±	23.0	15.3	-	110	17.0	±	7.87	6.04	-	39.1
Cation exchange capacity	$cmol_c$ kg^{-1}	27.7	±	8.53	14.7	-	49.7	13.8	±	4.08	7.89	-	25.4
Acid-oxalate extractable aluminum	g kg^{-1}	35.3	±	9.02	5.20	-	55.1	8.80	±	3.33	3.90	-	17.5
Phosphate absorption coefficient[a]	-	1770	±	290	560	-	2260	750	±	250	320	-	1410
Total nitrogen	g kg^{-1}	3.46	±	1.43	1.32	-	7.06	1.41	±	0.625	0.615	-	3.14
Soil available nitrogen[b]	mg kg^{-1}	33.9	±	11.4	15.5	-	95.5	47.3	±	14.9	26.3	-	88.5
Soil available phosphate	mg P_2O_5 kg^{-1}	230	±	99.0	72.0	-	611	409	±	139	190	-	887
Exchangeable potassium	mg K_2O kg^{-1}	324	±	121	111	-	673	343	±	119	120	-	630

[a] Phosphate absorption coefficient; conventional Japanese method for evaluating soil`s ability to make phosphate unavailable to crops.
[b] Soil available nitrogen; hot water extracted N. [c] SD; standard deviation.

Although total N was higher in Tokachi soils, the available N was higher in Kamikawa soils. Similarly, soil available P and K were higher in Kamikawa soils as compared to Tokachi soils (Table 4.1). We obtained records from farmers for each site on application rate of fertilizers. Results indicate that the mean N fertilizer rates used were 81 and 110 kg ha^{-1} in Tokachi and Kamikawa sites, respectively (Fig. 4.1a). The mean P fertilizer rates used were 244 and 210 kg P_2O_5 ha^{-1} in Tokachi and Kamikawa, respectively (Fig. 4.1b). The mean K fertilizer rates used were 102 and 110 kg K_2O ha^{-1} in Tokachi and Kamikawa, respectively (Fig. 4.1c).

4.4.2. Status of in-season NPK fertilizer application rates

To assess the status of nutrient in the soil, we compared the currently applied rates with the recommended fertilizer rates based on local Fertilizer guidelines (Table 4.2). After adjusting the recommended rates using soil-available nutrients information, we found that on 22% and 74% sites of Tokachi and Kamikawa districts, respectively, farmers applied higher than the recommended rates of N (Fig. 4.2a). Whilst 79% and 86% of farmers in Tokachi and Kamikawa districts, respectively, applied more phosphate fertilizers than recommendation rates (Fig. 4.2b). Similarly, K fertilizer application rates showed that 67% and 84% of growers Tokachi and Kamikawa districts, respectively, applied more K fertilizer than the recommendation rates (Fig. 4.2c). Potato tuber yields exhibited no response to in-season application of N, P, and K fertilizers (Table 4.3), except in Andover that where the yield was significantly reduced with increased N fertilizer rates. Similarly, potato tuber yields did not respond to soil available N, P, and K (Table 4.3) except in Andover where the yield was reduced with increased available P. From soil and tuber analyses, we were able to assess the influence of soil available nutrients as well as N, P, and K fertilizer application rates on tuber nutrients concentrations (Fig. 4.3). Overall, soil available N, P, and K were significantly and positively related to tuber N, P, and K concentrations (Fig. 4.3a, 4.3c and 4.3e). In contrast, in-season PK application rates were not related to P and K concentration in the tuber (Fig. 4.3d; 4.3f). However, N application rates were significantly and positively related to tuber-to-tuber N concentration except for cultivar Snowden (Fig. 4.3b).

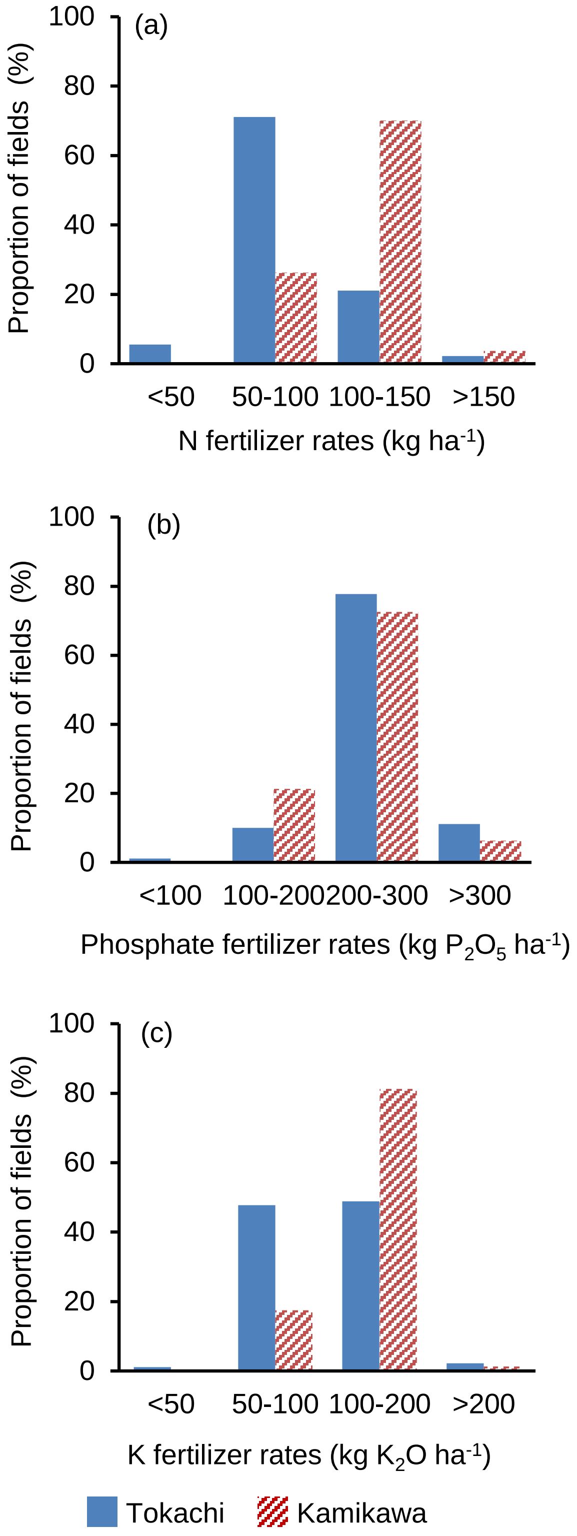


Figure 4.1. Histograms of (a) in-season growers nitrogen fertilizer application rates, (b) in-season growers phosphate fertilizer application rates, and (c) in-season potassium fertilizer application rates in Tokachi and Kamikawa districts.

Both P and K fertilizer application rates were not related to tuber P and K concentrations, except in the cultivar Snowden where increased rates of phosphate fertilizer application significantly reduced tuber P concentration (Fig. 4.3). Specific gravity was significantly and negatively related to tuber K concentrations (Fig. 4.4c).

Table 4.2. Location, soil type, standard fertilizer recommendations in Tokachi and Kamikawa districts.

			Standard fertilizer rates (kg ha^{-1})[a]		
Location	Soil type	Number of sites	N	P_2O_5	K_2O
Tokachi	Andisols	78	60	200	110
	Lowland soils	12	50	140	100
Kamikawa	Upland soils	72	80	180	110
	Lowland soils	8	50	140	100

[a]Standard fertilizer application rates recommended by Hokkaido Fertilizer Recommendations (Department of Agriculture, Hokkaido Government 2015). The major sources of N, P, and K fertilizers used in the two regions are ammonium sulfate, mono ammonium phosphate and potassium sulfate, respectively.

Also specific gravity was significantly and negatively related to tuber N concentrations except in the cultivar Andover (Fig. 4.4a). Whereas specific gravity was not related to tuber P concentration except in the cultivar Toyoshiro where there was a negative relationship (Fig. 4.4b).

4.4.3. Relationship between soil available NPK content and tuber NPK concentrations

The results of the present study suggest that tuber N, P and K concentrations are positively influenced by available N, P and K in the soil (Fig. 4.3a, 4.3c, 4.3e). Furthermore, the result also suggest that in-season P and K application rate did not influence the tuber P and K concentrations except in the cultivar Snowden where P application rate had negative influence on tuber P concentration. Additionally, our results indicate that soil available N had a positive influence on tuber N concentration in only two cultivars (Toyoshiro and Kitahime) and no influence on two cultivars (Andover and Snowden; Fig. 4.3a). Similarly, in-season N application rate had positive influence on tuber N concentration except the cultivar Snowden (Fig. 4.3b). The information on the relationship between tuber N, P and K concentration and available N, P, and K in the soil is lacking in the literature.

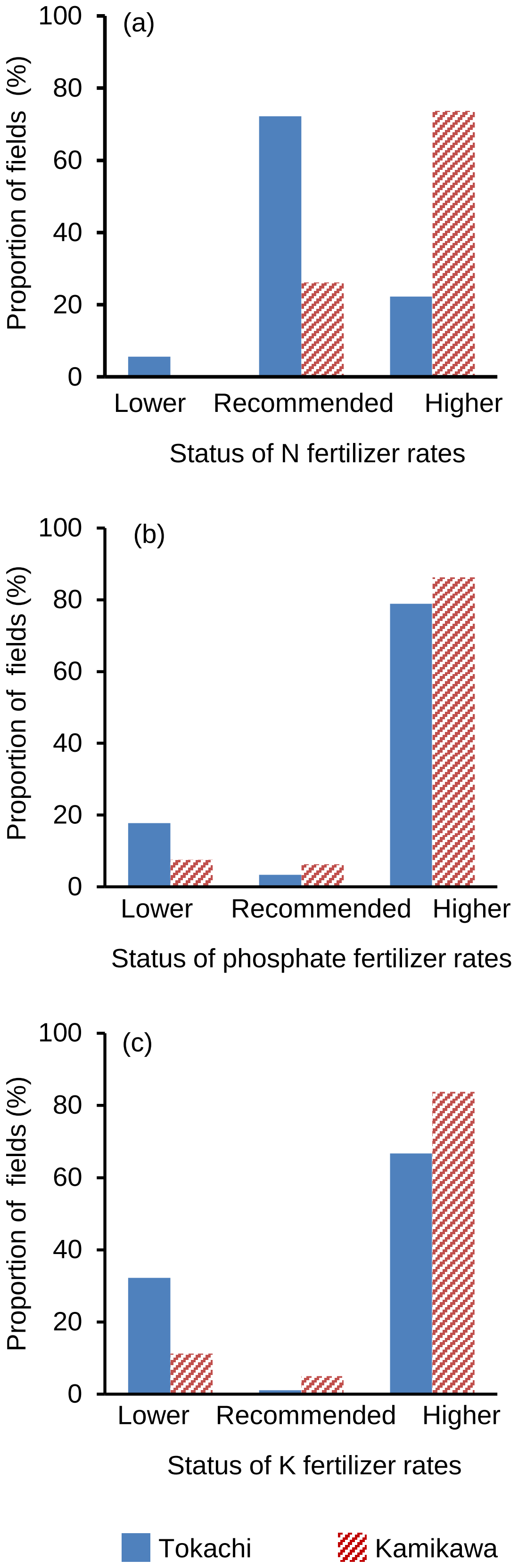


Figure 4.2. Status of current growers fertilizer rates compared with soil test recommendation for upland crop production in Hokkaido region (Department of Agriculture, Hokkaido 2015).

In our study we analyzed paired soil and tuber samples obtained from the same 170 separate commercial production sites. These paired sample analysis gave us the opportunity to evaluate such relationships between soil nutrient availability and tuber nutrient concentrations. We do not have an exact explanation as to why high available N, P, K in the soil are positively related to tuber N, P, and K concentration (Fig. 4.3b; 4.3d and 4.3f). Past studies have established that potato tuber and stolons have roots that transport Ca from the surrounding soil solution to the tuber independent of the plant (Kratze and Palta 1985; Busse and Palta 2006; Palta 2010). We don't know whether N, P, and K are also in part taken up by tubers independent of the plant, future studies should focus on understanding the possibility of tuber roots to also absorb N, P, and K from the soil solution and transport to the tuber. So far, it is believed that most plant nutrients including N, P and K in potato plant moves from shoot to tubers during growth, final bulking stage, and during canopy senescing (Houghland 1960; Allison et al. 2001a). Kang et al. (2014) reported occurrence of luxury absorption of K by the potato plant with high K availability in the media. The observed strong relationship between soil available N, P, and K and tuber N, P, and K concentration suggests that potato crop take more NPK than it is required.

Table 4.3. Pearson correlation matrix of potato tuber yield, soil available nutrients, and in-season fertilizer application rates.

		Soil nutrient levels			In-season fertilizer application rates		
		N	P_2O_5	K	N	P_2O_5	K
Tuber yields	All cultivars	-0.218*	-0.0085	0.0805	-0.143	0.142	-0.0511
	Andover	0.109	-0.282*	0.248	-0.470**	-0.241	0.192
	Toyoshiro	-0.200	0.107	-0.0293	-0.277	-0.0012	0.199
	Kitahime	-0.150	0.135	-0.0170	0.0601	0.110	0.146
	Snowden	0.0753	0.0773	-0.0030	0.189	0.156	0.210

*, **; Indicate significant difference at $p < 0.05$ and *0.01*, respectively.

However, high N fertilizer rates have been associated with high tuber amino acids including asparagine that increases acrylamide forming potential during chip processing (Painter and Augustine 1976; Rosen et al. 2018). Because acrylamide is associated with human neurotoxins and carcinogen, there is a health safety concern about the need to reduce acrylamide in human food.

In general, results of our study suggest a negative relationship between specific gravity and tuber N and K concentrations except in the cultivar Andover where no relationship was found between tuber N and specific gravity (Fig. 4.5). Chip processing industry requires tubers with good quality such as high specific gravity that result in higher product yield per unit fresh mass and improved quality products (Mosley and Chase 1993). According to Sun et al. (2017), specific gravity ranges from 1.080 to 1.089 are desired for high quality potato chip products. Our results show that 53, 12, 8 and 22% of sites (farmers) of cultivars Andover, Toyoshiro, Kitahime and Snowden, respectively, had specific gravity lower than the required range for processing (Table 4.4). Interestingly, high proportion of fields with specific gravity lower than the recommended range was observed in foreign cultivars (Andover and Snowden). The low specific gravity of these cultivars under local conditions suggests that the tuber attribute is not only influenced by cultivar but also other factors.

4.4.4. Relationships between tuber NPK concentration and specific gravity

Past studies have shown confounding results about the influence of N, P, and K fertilizer rates on specific gravity. Several studies on N fertilizer rates that included specific gravity evaluations summarized by Laboski and Kelling (2007) indicated variable effects of either no effect of N fertilizer rate, or decrease in specific gravity with increasing N fertilizer rates. In the same review, they concluded that the effects of N on specific gravity appeared to be a major factor when fertilizer rates exceed the needs of a plant. Other studies have also found depressive effects of tuber N concentration on tuber dry matter and specific gravity caused by increasing N application (Zelalem et al. 2009). However, Joern and Vitosh (1995) did not observe any effect of N fertilizer on dry matter even at the highest N application. The observed decreasing trend in specific gravity with increase in tuber N could be attributed to N stimulating excess vine growth more than tuber growth that resulted in low dry matter concentration. Alternatively, N is associated with Gibberellin biosynthesis, and high Gibberellin levels inhibit tuberization (Abdalla et al. 1995) and impede accumulation of starch in tubers (Vreugdenhil and Sergeeva 1999).

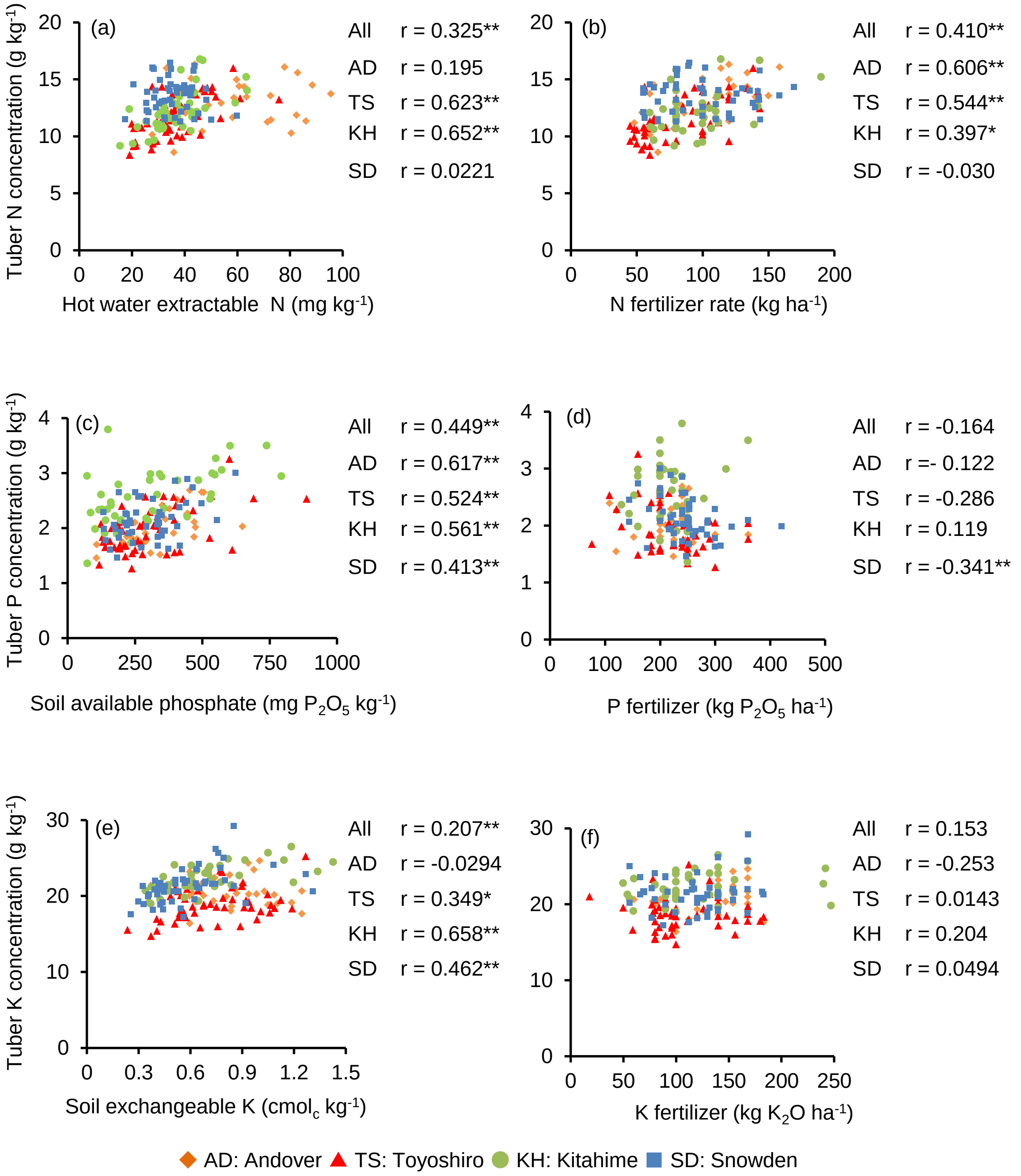


Figure 4.3. Relationships between (a) hot water extractable N and tuber N concentration,(b) N fertilizer rates and tuber N concentration, (c) soil available phosphate and tuber P concentration, (d) phosphate fertilizer rates and tuber P concentration, (e) soil exchangeable K and tuber K concentration, and (f) K fertilizer rates and tuber K concentration for all cultivars combined and separated. r = Pearson correlation coefficient, *, ** indicate significant relationships between variables at $p < 0.05$ and $p < 0.01$, respectively.

The observed negative relationship between tuber K concentration and specific gravity can be an indication of excess K in tubers (Fig. 4.4c). Previous studies have reported that K fertilizer rate was inversely related to either yield or tuber specific gravity (Allison et al. 2001a). In the same study, they observed that when applied at recommended rate the influence of K fertilizer on dry matter was nonsignificant. However, application of K fertilizer in excess of the recommendation rate caused reduction in dry matter content. Although K is required for sugar translocation and starch synthesis, high concentration of K in tubers promotes moisture accumulation resulting in decreased specific gravity (Westermann 2005; Kumar et al. 2007). Studies have suggested that 18 g kg^{-1} of tuber K concentration may result in optimum quantity of dry matter for chip processing potatoes (Westermann and Tindall 2000). In the current study, 86% of the fields had tuber K concentration exceeding 18 g kg^{-1}. This suggests increased risks of reducing specific gravity of tubers. Past studies have also compared the effects of different rates of KCl and K_2SO_4 on tuber yields and specific gravity (Kumar et al. 2007; Westermann et al. 1994). These workers found that KCl lowered specific gravity more than K_2SO_4 due to higher salt index. Since K_2SO_4 is the only recommended form of K fertilizer in Hokkaido region (Table 4.2), we did not assess the effects of K-source on specific gravity.

Interestingly tuber P concentration was not related to specific gravity except in the cultivar Toyoshiro where there was a negative relationship (Fig. 4.4b). Studies on the evaluation of the effects of P fertilizer rates on specific gravity have shown variable results. Addition of P fertilizer on soils testing low in available P has been shown to increase total solids and dry matter content because P is required for synthesis and storage of starch in tubers (Houghland 1960; Alvarez-Sanchez et al. 1999). However, under high availability of soil P, application of P fertilizer had nonsignificant effect on specific gravity (Rosen and Bierman 2008). Although P is important for phosphorylation of starch in tubers, excessive P is associated with faster closure of canopy and shorten the growing period (Sommerfeld and Knutson 1965; Sharma and Arora 1988).

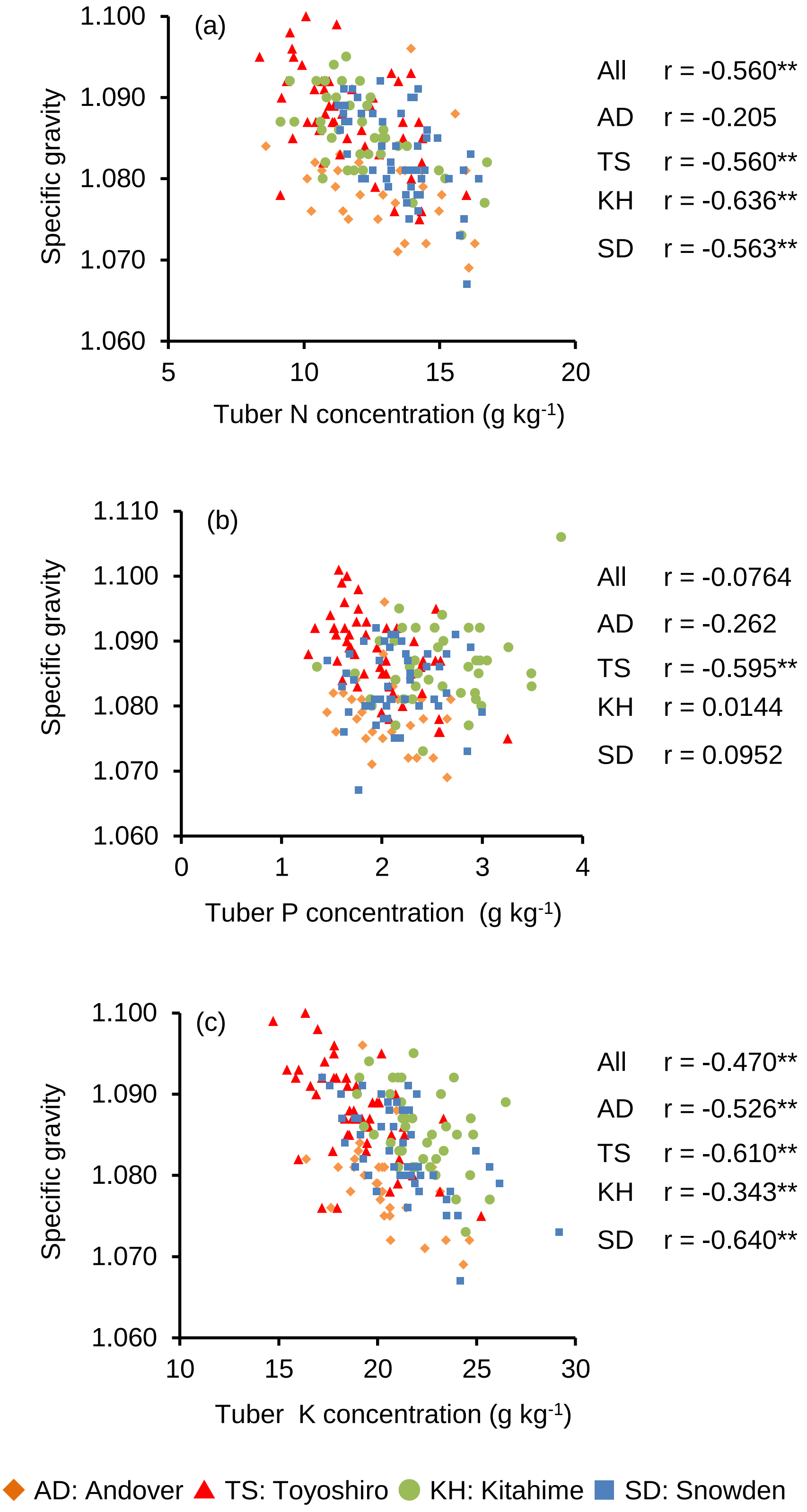


Figure 4.4. Relationships between specific gravity and (a) tuber N concentration, (b) tuber P concentration, and (c) tuber K concentration for four cultivars combined (n = 170) and separated. r = Pearson correlation coefficient, asterisks indicate significant relationships between variables at $p < 0.01$ (**).

4.4.5. Relationship between fertilizer application rates and tuber yields

Hokkaido fertilizer recommendation has established base standard fertilizer application rates (Table 4.2; Department of Agriculture, Hokkaido Government 2015), and farmers are required to either add on or subtract from the base rate depending on the soil test. We found that irrespective of the high soil available N, P and K, farmers are still applying more than the standard rates recommended by Hokkaido recommendation (Fig. 4.2). The gap between standard rate and farmers' rate was significantly wider in Kamikawa compared to Tokachi fields (Fig. 4.2). This explains in part the reason why concentration of available nutrient is higher in Kamikawa region (Table 4.1). In case of soil available P, the lower soil available P in Tokachi is partly caused by higher Al_o contents and associated with higher PAC in these Andisols (Table 4.1) which have high ability to adsorb applied phosphate and make it unavailable to crops (Tani et al. 2010).

We found in general no yield response to soil available nutrients and in-season N, P and K fertilizer applications (Table 4.3). This is consistent with a several studies that did not find any yield response to N, P, and K fertilization on soils testing high on these nutrients (Allison et al. 2001a; AbdeGadir 2003; Belanger et al. 2002; Hochmuth et al. 2002; Kang et al. 2014). Hopkins et al. (2018) indicated that there is a diminishing response of crop yield to increasing rates of fertilizers with an eventual plateau of no added response. The observed lack of yield response in the current study can be attributed to high availability of N, P, and K in the soil that obscured the relationship between yields and fertilizers (Table 4.1). The results suggest that under high soil available NPK, addition of NPK fertilizers does not increase yields. Paulo (2010) and Maltas et al. (2018) observed a positive yield response to increased rates of N fertilizer, although soil tests for N were low. The reduction in yield in Andover cultivar may be because of the fact that excessive N promotes vegetative growth more than tuber growth. Andover is a short season cultivar thus excessive canopy growth may be detrimental to tuber in this cultivar. The results of phosphate fertilizer rates on tuber yields from the current study sites were earlier reported (Gondwe et al. 2017).

Table 4.4. Potato yield and specific gravity data from Tokachi and Kamikawa farmer fields.

Location	Cultivar	Number of	Tuber yield (Mg ha^{-1})						Specific gravity					
		sites	Mean		SD	Range			Mean		SD	Range		
Tokachi	Andover	10	41	±	6.4	34	-	54	1.080	±	0.002	1.076	-	1.084
	Toyoshiro	30	46	±	5.7	36	-	65	1.089	±	0.006	1.078	-	1.101
	Kitahime	20	41	±	7.0	28	-	53	1.085	±	0.007	1.073	-	1.106
	Snowden	30	43	±	6.0	32	-	54	1.081	±	0.050	1.067	-	1.090
Kamikawa	Andover	20	35	±	11	22	-	56	1.078	±	0.006	1.069	-	1.096
	Toyoshiro	20	44	±	5.8	33	-	54	1.087	±	0.007	1.075	-	1.099
	Kitahime	20	43	±	6.9	33	-	57	1.087	±	0.005	1.077	-	1.095
	Snowden	20	46	±	7.7	39	-	68	1.086	±	0.005	1.073	-	1.092

Generally, our results agreed with other studies (Hochmuth et al. 2002; Fernandes and Sorrato 2016) that did not find yield response to application of P fertilizer in soils with high P availability. While Fernandes and Sorrato (2016) did not see any change in tuber numl size, Sommerfeld and Knutson (1965) found a reduction in yield in more than 50% cases where excess P was applied. They suggested that excessive use of phosphate fertilizer resulted in reduced size of tubers by hastening maturity period. Generally, the potato yields in the current study were higher than the current national average (FAO 2014).

It is noteworthy that in addition to influencing tuber yield and quality, excess NP fertilizer rates in non-responsive soils such as those of Tokachi and Kamikawa region poses a high risk of nonpoint pollution. Excess N input over output in an agroecosystem may lead to losses though volatization, denitrification, leaching and runoff that can cause air and water pollution (Vos 1997). Similarly, phosphate in dissolved form in runoff water or adsorbed form on eroded soil particles can cause water quality degradation in streams, rivers and lakes (Ruark et al. 2014). Our results suggest that farmers need to apply fertilizers based on recommendation to reduce the potential environmental degradation associated with excessive fertilization.

4.5. Summary

The study suggests that in general soil available N, P, and K increases tuber N, P, and K concentrations and tuber N and K concentrations can reduce specific gravity. Interestingly, tuber P concentration had no effect on specific gravity. Our results also suggest that application of N, P, and K fertilizers in excess of recommended rates on soils that are already rich in these nutrients does not increase tuber yields. Our results suggest that farmers need to apply fertilizers based on recommendation to reduce the potential environmental degradation associated with excessive fertilization.

CHAPTER 5. SOIL AND TUBER CALCIUM AFFECTING TUBER QUALITY OF PROCESSING POTATO (*SOLANUM TUBEROSUM* L.) CULTIVARS

5.1. Abstract

Calcium (Ca) nutrition for potato (*Solanum tuberosum* L.) is important to increase tuber Ca concentration and improve potato tuber yield and quality. High tuber Ca content among other benefits mitigates incidence of blackspot bruise through maintenance of membrane health and regulation of biochemical reactions that leads to potato tuber discoloration. However, growers avoid application of Ca fertilizer in potato production in the belief that it causes potato common scab in Hokkaido, Japan. This study was conducted in Hokkaido, to determine the current status of soil Ca and tuber Ca content levels, and its effect in mitigating incidence of potato bruise. Soil and tuber samples were collected from 90 and 80 fields in Tokachi and Kamikawa districts, respectively, in 2013 and 2014. Soil samples were analyzed for base saturation, Ca saturation and exchangeable Al. Tuber Ca content and susceptibility of tubers to bruising were also evaluated. The study found that (1) 81 and 76 % of soils collected from Tokachi and Kamikawa district, respectively, were deficient in Ca level, (2) tuber Ca content was lower than the reported value (250 mg kg^{-1}) considered to mitigate incidence of bruise, and (3) incidence of bruise were influenced by both tuber specific gravity and Ca content. There is urgent need to apply Ca fertilizer to attain increased soil Ca levels and improve quality of tubers.

Key words: processing potato, blackspot bruise, soil Ca, tuber Ca, tuber quality.

5.2. Introduction

The importance of calcium (Ca) in plant nutrition has been well established (Marschner 1995; Palta 1996; White and Broadley 2003). Being a divalent cation, it is required in the cell wall and membranes as well as a counter-cation for anions in the vacuole, and as an intracellular messenger in the cytosol (White and Broadley 2003). Ca is an integral part of the cell wall where it provides strength and stability by forming intra-molecular linkages between pectin molecules. In the cell membrane, Ca bridges phosphate and carboxylate groups of phospholipids head groups and, thereby, provides stability to the membrane (Legge et al. 1982). Selective permeability of cell membrane cannot be maintained in absence of sufficient level of Ca around the membrane. Reduction in Ca associated with cell membrane result in leaking of cellular salts and organic compounds that eventually lead to death of the cell (Harris and Palta 1999). Cytosolic Ca provides a cellular signal that regulates metabolism and mediates plant responses to environmental and biotic stress (Palta 1996).

In potato (*Solanum tuberosum* L.) production, Ca is a critical nutrient for growth and development of potato tubers. Adequate supply of Ca fertilizer improves potato tuber size, grade, and yield (Simmons et al. 1988; Ozgen and Palta 2005). Other studies have provided evidence linking tuber quality to Ca nutrition (Karlsson and Palta 2006). Desired quality in produced potatoes depends upon the type of final product (Harris 1992). Potato tubers with less internal defects (such as internal brown spot and hollow heart) and blackspot bruise are desired by the processing industry (Corsin et al. 1999; Steyn et al. 2009). The presence of these defects in potatoes reduces tuber quality and market value resulting in economic loss to growers and processors (Clough 1994).

Blackspot bruise is one of the major causes of quality loss in processing potato industry (Corsini and Thornton 1999). They occur as a result of a mechanical impact that damages intra-cellular membranes (Corsin et al. 1992). This allows phenols to come into contact with polyphenol oxidase (PPO) that consequently produces melanin that causes dark pigment. Development of blackspot bruise depends on the mechanical impact and susceptibility of tubers to an impact (Corsini and Thornton 1999). Structural properties of tubers influence its resistance to blackspot bruise (Laerke et al. 2002). Ca has been shown to maintain health of cell membrane and its integrity. Other studies provided evidence that in-season Ca fertilizer application did not only increase tuber Ca content but also improved tuber quality with reduced incidences of blackspot bruise (Karlsson and Palta 2006). The increase in tuber Ca from 100 to 250 mg kg^{-1} resulted in about 50 % reduction in the incidence of bruise (Fig. 5.1).

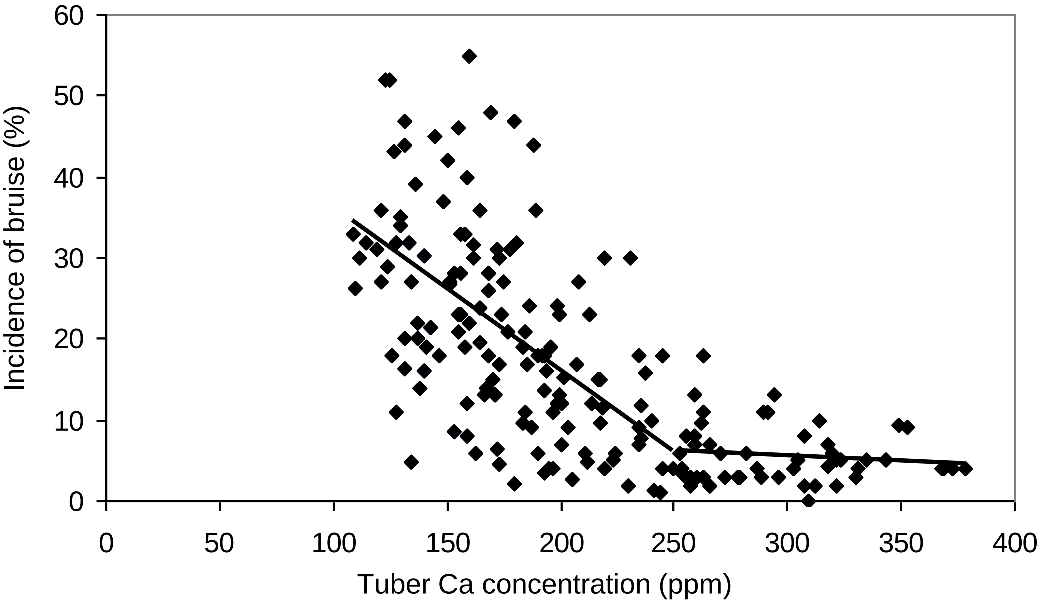


Figure 5.1. Relationships between tuber Ca concentration and incidence of blackspot bruise of potato tubers. Source: Karlsson et al. (2006).

Although Hokkaido fertilizer recommendation provides guidelines for optimal soil Ca saturation (40 to 60 %; Department of Agriculture, Hokkaido Government 2015), there is no provision for Ca fertilization to supplement the soil Ca. It is not clear why Ca fertilizer recommendation is not included in the guidelines. In part, this could be related to the common belief that Ca containing fertilizer especially lime increases outbreak and development of common scab (Goto 1985). Common scab is a soil borne disease that is found in most potato production areas worldwide (Pavlista 2005). Presently, growers manage common scab disease by maintaining relatively low soil pH that minimizes its occurrence. Soil pH below 5.3 is believed to suppress the growth of common scab causing pathogens (Mizuno and Yoshida 1993). Since liming of soils is associated with increases in soil pH, growers avoid the application of Ca containing fertilizers in potato production. While soil pH is strongly related to severity of common scab, this relationship is often influenced by other soil conditions (Lambert and Manzer 1991; Mizuno et al. 1998; Lambert et al. 2005). Mizuno and Yoshida (1993) found that common scab development in Andisols of Hokkaido to be influenced by soil exchangeable aluminum (Al) content rather than soil pH. In that work, soil exchangeable acidity (Y_1) was considered to be a more reliable parameter compared with soil pH for suppressing common scab. This shows that maintaining low soil pH for suppressing common scab is only effective in particular soil types. Moreover, the idea of using low soil pH levels to control common scab may have detrimental effects on the productivity of potato crop and subsequent crops in the rotation.

Apparently, growers in Hokkaido have concentrated much effort in common scab disease prevention at the expense of avoiding Ca fertilizer application. It remains unclear whether there is sufficient Ca in the potato growing fields to support potato tuber`s unique nutritional needs. Therefore, the objectives of this study were to i) understand the present status of soil and potato tuber Ca content levels of the samples collected from two major potato producing districts, ii) assess the effects of soil Ca content on the tuber Ca content, and iii) investigate the relationship between tuber Ca content and susceptibility of potato tubers to develop blackspot bruise.

5.3. Materials and methods

5.3.1. Study site

A two-year soil and potato tuber survey was conducted in 2013 and 2014 growing seasons in Tokachi and Kamikawa districts (Fig. 2.1 in chapter 2). The two districts were purposely chosen for this study because they are among the major potato producing districts, accounting for 41 and 6 % of the total production in Hokkaido, respectively (MAFF 2016). The districts have distinctively different soil characteristics; the dominant soil type in Tokachi is volcanic ash soils known as Andisols that account for 57 % of the total production area whilst Kamikawa district is dominated by soils of pyroclastic flow deposit origin classified as Inceptisols (Cultivated Soil Classification Committee 1995; Hashimoto 2008).

We selected 90 and 80 fields in Tokachi and Kamikawa districts, respectively. The selected fields represented typical of growing fields used for potato production in the region. The selected cultivars are Andover (n = 30), Toyoshiro (n = 50), Kitahime (n = 40), and Snowden (n = 50) to represent popular cultivars used for processing in the region. Growers in this region typically practice a four-year rotation of potato, winter wheat (*Triticum aestivum*), sugar beet (*Beta vulgaris*), and soybean (*Glycine max*).

5.3.2. Potato and soil sampling design

On each of the selected study field, sampling plot of 5-m row length was established where plant stand was relatively uniform (no missing plant). The size of each selected plot was three rows wide and 15 plants long, with a 75 cm row interval and 30 cm plant interval. The sampling plot was placed at least 3 m away from the boundary and tractor paths to avoid border effects. Areas close to the ditches and manure damps were also avoided. As a result of the crop-rotation sequences, different potato study fields were used each year. Potatoes were mostly preceded by soybean and sugar beet in Tokachi district, and sugar beet and winter wheat in Kamikawa district.

Soil samples were collected at flowering stage from two side rows. Ten sub-samples (5 samples from each row) were collected from 0-20 cm depth between the planting stations. The collected soil samples were thoroughly mixed and composited into one single soil sample for analysis.

Potato tubers were harvested by hand from all 15 plants in middle row, and tuber heavier than 20 g were weighed to obtain yield per plot.

5.3.3. Soil and potato tuber analyses

Soil samples were air dried and passed through a 2-mm sieve before chemical analysis. The soil pH was measured with a glass electrode using 1 : 2.5 soil/water solution. The cation exchange capacity (CEC) and exchangeable Ca were measured by ammonium acetate method buffered at pH 7 as described by Schollenberger and Dreibelbis (1930). Ca saturation was determined as the ratio of exchangeable Ca to CEC multiplied by 100 %. Water soluble Ca was measured by shaking 1: 5 soil/water solution for one hour, and quantified by atomic absorption spectrophotometer (AAS;

Z-5010, Hitachi Corporation, Tokyo, Japan). Total carbon (TC) content was assessed on grounded samples and the measurement was undertaken using a dry combustion method with a Vario EL III analyzer (Elementar Analysensysteme, Hanau, Germany). Exchangeable acidity (Y_1) was measured by shaking 1 : 2.5 soil/1 mol L^{-1} KCl solution for one hour, and the extract was titrated with 0.1 mol L^{-1} NaOH using phenolphthalein as an indicator as described by Mizuno and Yoshida (1993). Exchangeable Al in the KCl extract was quantified by inductively coupled plasma emission spectroscopy (ICP-AES, ICPS-8100, Shimadzu Corporation, Kyoto, Japan).

Tuber samples were peeled, diced, and dried in oven at 80°C for four days until a constant weight was reached. Tuber Ca was determined using acid (H_2SO_4/H_2O_2) digested samples, and quantified by ICP-AES (ICPS-8100, Shimadzu Corporation, Kyoto, Japan).

5.3.4. Determination of blackspot bruise susceptibility

A representative sample of 50 tubers per field weighing between 120 and 190 g were used for evaluating susceptibility potato tubers to bruising. Medium sized tubers were used in the study to minimize the effect of size on the mechanical properties and impact energy relationships. Tubers were kept at 4°C prior to blackspot bruise evaluation.

Weight dropping method was used to evaluate potato tuber susceptibility to blackspot bruise. In this method, tubers were bruised by dropping a steel plunger weighing 100 g (Fig. 5.2a) with a head curvature radius of 22 mm through a vertical guiding tube from a height of 50 cm (Fig. 5.2b). The bruised site on the stem end was clearly marked with a marker on the surface of the tubers. The marked site was hand peeled using a knife after incubation at 24°C for 48 hours. Tubers were then cut and examined for the incidence of blackspot bruise and internal quality. Blackspot bruise on each tuber was subjectively evaluated on 0 to 3 scale based on the intensity of discoloration (Fig. 5.4). Level 0 means no discoloration or blackening and level 3 means discoloration of diameter between 5 and 10 mm and depth less than 5 mm as outlined by Dwelle et al. (1977). Blackspot bruise incidences were defined as proportion of tubers subjected to the impact that ranked from level 1 to 3.

(a) Steel plunger (b) Vinyl chloride pipe (c) Bruising experiment

Figure 5.2. Photographs of (a) steel plunger used to develop bruising, (b) vinyl chloride pipe, guiding tube through which a plunger was dropped and (c) dropping of a plunger to develop bruise.

5.3.5. Statistical analyses

Statistical analyses were carried out using Excel Statistics 2012 (Social Survey Research Information, Tokyo, Japan). Descriptive statistics for the measured soil properties were calculated. Analysis of variance (ANOVA) was completed on the main effects and interaction effects, effects were considered significant at 0.05 probability level. Significant mean was tested using Tukey's honest significant difference (HSD) test. Pearson correlations were calculated to determine the extent of relationships among soil Ca, tuber Ca concentration, specific gravity, and incidence of bruise.

5.4. Results and discussion

5.4.1. Soil characteristics and current status of calcium of the studied fields

The detailed classification of the soils for the study fields was described in our previous study (Gondwe et al. 2017). Generally, soil samples from Tokachi and Kamikawa districts displayed a distinctive difference in soil characteristics. The dominant soil type in Tokachi district was Andisols (86 % of the fields) and Inceptisols in Kamikawa district (90 % of the fields). The remainder in both districts was classified as Entisols. TC was significantly higher in Tokachi district, ranging from 15.3 to 110 g kg^{-1}, compared to Kamikawa district they ranged from 6.04 to

39.1 g kg^{-1}.

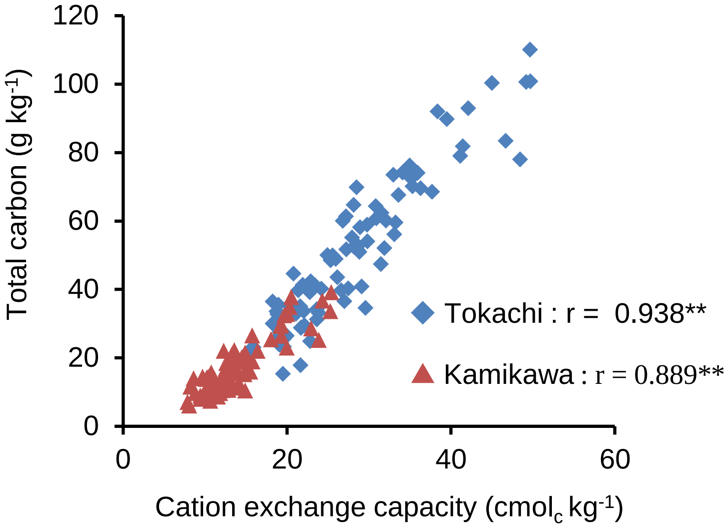


Figure 5.3. Relationship between cation exchange capacity of the soil and total carbon for the study fields in Tokachi (n = 90) and Kamikawa district (n = 80).

The mean values of CEC were about twofold in Tokachi district (27.5 cmol$_c$ kg^{-1}) compared to Kamikawa district (13.8 cmol$_c$ kg^{-1}; Table 1). CEC indicates negatively charged surfaces of clay and humic substances that attract and holds cations in the soil (Nyaganti and Culman 2017). The difference in CEC between the two districts originates in differences in organic matter content as indicated in TC content (Table 5.1) as well as difference in clay mineral content and types.

Soil pH in Tokachi district varied from 4.9 to 6.1 (mean = 5.4) and 4.8 to 6.0 (mean = 5.3) in Kamikawa district (Table 5.1). The recommended soil pH for upland crop production in Hokkaido is from 5.5 to 6.5 (Department of Agriculture, Hokkaido Government 2015). The results demonstrate that 54 and 60 % of soil samples from Tokachi and Kamikawa district, respectively, had soil pH below the recommended range (Fig. 5.4b).

Base saturation ranged from 20.1 to 80.6 % (mean = 42.6 %) in Tokachi district and 22.8 to 90.4 % (mean = 52.1 %) in Kamikawa district (Table 5.1). In Hokkaido region, base saturation from 60 to 80 % is recommended for upland crop production (Department of Agriculture, Hokkaido Government 2015).

Table 5.1. Descriptive statistics of the selected soil properties of growers fields in Tokachi and Kamikawa districts.

Soil property	Unit	Tokachi (n = 90)						Kamikawa (n = 80)					
		Mean		SD[a]	Range			Mean		SD	Range		
pH (H_2O)	-	5.4	±	0.26	4.9	-	6.1	5.3	±	0.34	4.8	-	6.0
Total carbon	g kg^{-1}	49.8	±	23.0	15.3	-	110	17.0	±	7.87	6.04	-	39.1
Cation exchange capacity	$cmol_c$ kg^{-1}	27.5	±	8.29	14.7	-	49.7	13.8	±	4.07	7.89	-	25.4
Base saturation	%	42.6	±	11.4	20.1	-	80.6	52.1	±	15.5	22.8	-	90.4
Exchangeable calcium	$cmol_c$ kg^{-1}	9.07	±	3.84	2.71	-	21.4	4.68	±	2.87	1.43	-	16.5
Calcium saturation	%	32.8	±	9.7	14.9	-	61.8	33.3	±	12.4	10.1	-	68.9
Exchangeable aluminum	$cmol_c$ kg^{-1}	0.15	±	0.20	0.0	-	0.93	0.20	±	0.23	0.0	-	0.92
Exchangeable acidity (Y1)		2.2	±	1.5	0.12	-	7.14	2.9	±	2.0	0.18	-	7.4

[a]SD; standard deviation.

The results of the study revealed that 91 % and 69 % of the soils collected Tokachi and Kamikawa districts, respectively, had base saturation lower than the recommended range (Fig. 5.4a). Exchangeable Ca ranged from 2.71 to 21.4 cmol$_c$ kg^{-1} (mean 9.07 cmol$_c$ kg^{-1}) in Tokachi district and 1.43 to 16.5 cmol$_c$ kg^{-1} (mean 4.68 cmol$_c$ kg^{-1}) in Kamikawa district (Table 5.1; Fig 5.5a). Conventionally, fertility status of Ca in the uplands soils of Hokkaido is evaluated based on the proportion of CEC occupied by Ca ions (Ca saturation). Sharpley and Kamprath (1988) demonstrated that saturation of soil exchangeable complex of cations characterizes soil cation availability better as it represents both intensity and buffering factors. Soil Ca saturation between 40 to 60 % is considered sufficient to support crop production in upland fields of Hokkaido (Department of Agriculture, Hokkaido Government 2015). We discovered that many of the fields in both districts had Ca saturation lower than the recommended range.

Generally, Ca saturation in the current study ranged from 14.9 to 61.8 % (mean = 32.8 %) in Tokachi district, and 10.1 to 68.9 % (mean = 33.3 %) in Kamikawa district (Table 5.1).

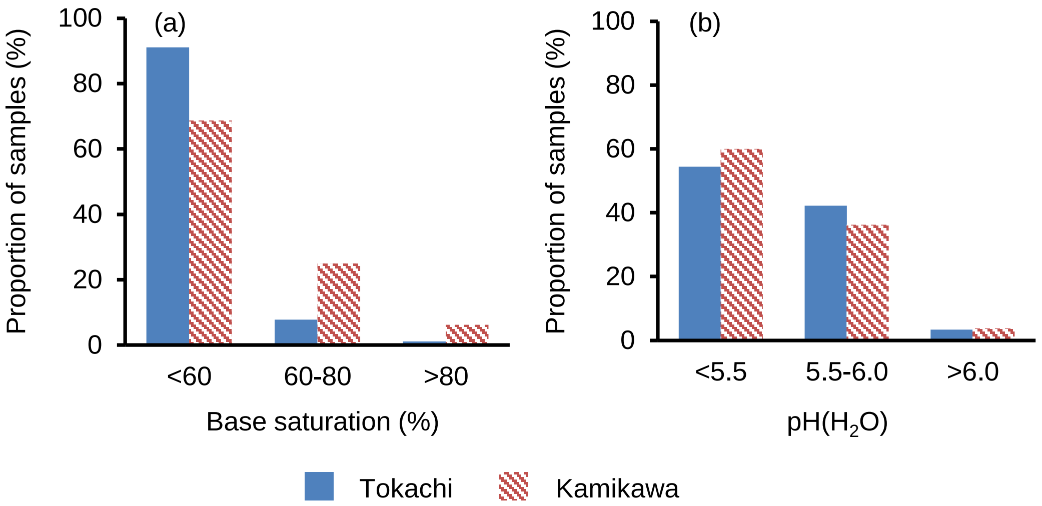


Figure 5.4. Frequency distribution of (a) base saturation and (b) pH (H_2O) of soil samples collected from Tokachi and Kamikawa districts in 2013 and 2014 growing seasons.

Exchangeable Ca was higher in Tokachi compared to Kamikawa but the Ca saturation values were almost equivalent. This is because Tokachi soils had nearly twofold higher CEC than Kamikawa soils (Table 5.1). To assess the status of soil Ca content, we categorized Ca saturation samples based on critical values, < 40 % (low), 40 to 60 % (optimum) and > 60 % (excess), indicated in Hokkaido Recommendation Guidelines (Department of Agriculture, Hokkaido Government 2015; Fig. 5.5b). The results demonstrated that 81 % and 76 % of soil samples from Tokachi and Kamikawa districts, respectively, had Ca saturation lower than the recommended critical range (40 to 60 %).

This showed a severe deficiency of Ca in the soils for adequate growth of potatoes. This result may be because growers tend to avoid application of Ca containing fertilizers. Goto (1985) suggested that increases in soil exchangeable Ca induces scab development but no other study supports this interpretation. Lambert and Manzer (1991) tested this hypothesis by applying dolomitic lime equivalent to 960 kg Ca ha^{-1}, and observed no relationship between increases in soil exchangeable Ca and scab development. Effects of lime application on outbreak of common scab disease are often related to changes in soil pH rather than Ca itself.

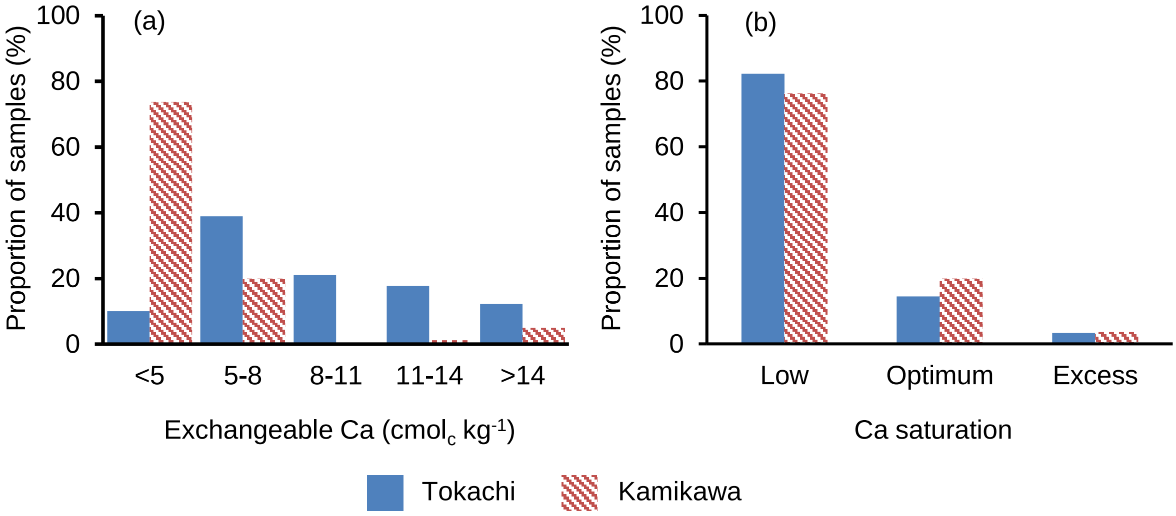


Figure 5.5. Frequency distribution of (a) exchangeable Ca and (b) Ca saturation of soil samples collected from Tokachi and Kamikawa districts in 2013 and 2014.

Past studies have demonstrated that application of gypsum increases exchangeable Ca without affecting either soil pH or scab index (Lambert and Manzer 1991). In the same study, addition of Ca in form of lime increased both pH and scab index.

Maintaining soil pH out of common scab tolerance range is recognized as an effective way of suppressing the disease (Lacey and Wilson 2001). A detailed study on the relationship between soil pH and the severity of common scab revealed that soil pH is not the direct cause of the disease (Mizuno and Yoshida 1993). The study showed that the effect of soil pH on development of common scab disease was an indirect effect of exchangeable Al. They demonstrated that at soil pH 5.3, it was possible to suppress common scab with exchangeable acidity Y_1 between 7 and 8, however, at similar pH and exchangeable acidity Y_1 between 3 and 4, decreasing soil pH did not suppress common scab. In support of this conclusion, Goto (1985) did not find any corresponding increase in scab index with application of dolomite from pH of 4.8 through to 5.0 in volcanic ash soils. Al becomes available at low pH and causes toxicity problems if exchangeable Al is high in the soil solution. Exchangeable Al greater than 2 $\text{cmol}_c\ \text{kg}^{-1}$ is considered to be high enough to affect plant growth in Andisols (Saigusa et al. 1980). In the current study, no sample had exchangeable Al greater than 2 $\text{cmol}_c\ \text{kg}^{-1}$ (Table 5.1). This could be bacause Andisols are dominated by non-exchangeable Al species that are not easily displaced even at low pH. Even Inceptisols and Entisols showed low Y_1 in the current study. The Entisols of Tokachi could be affected by volcanic ash whereas all soils in Kamikawa had not been influenced by volcanic ash. The concept of using low pH levels to control common scab appeared not be effective in all soils collected in this study.

5.4.2. Potato tuber Ca concentration

Tuber Ca content in Tokachi district varied between 67 to 218 mg kg^{-1} for all cultivars. The highest mean Ca content was found for Snowden (mean = 139 mg kg^{-1}) followed by Andover (mean 135 mg kg^{-1}), Kitahime (mean = 129 mg kg^{-1}), and Toyoshiro (mean = 114 mg kg^{-1}; Fig. 5.6a). For Kamikawa district, tuber Ca varied between 46 to 198 mg kg^{-1} for all cultivars. The highest mean Ca content was found for Kitahime (mean = 124 mg kg^{-1}) followed by Andover (mean 119 mg kg^{-1}), Snowden (mean = 110 mg kg^{-1}), and Toyoshiro (mean = 107 mg kg^{-1}; Fig. 5.6b). The results revealed different tuber Ca concentration among the cultivars that may have been caused by differences in dry matter yields rather than differences in relative ability of cultivars to assimilate

Ca to tubers. The interactive effects resulted from the differences in tuber Ca observed between the two growing seasons (Table 5.2). Higher Ca concentration was observed in 2013 compared to 2014 due to lower tuber yield (data not shown). Pooled data from all cultivars based on location showed relatively higher tuber Ca content in Tokachi (mean 129 mg kg^{-1}) than Kamikawa district (mean 115 mg kg^{-1}; data not shown). This observation corresponded with soil exchangeable Ca (Table 5.1). Simons and Kelling (1987) found a significant variation in tuber Ca across different soil types.

Past studies have demonstrated that tuber Ca concentration between 200 to 250 mg kg^{-1} was able to minimize incidence of bruise (Fig. 5.1; Karlsson and Palta 2006). In the current study, the overall average tuber Ca concentration was 122 mg kg^{-1} (ranged from 46 to 218 mg kg^{-1}), only four out of 170 samples had their tuber Ca concentration exceeding 200 mg kg^{-1} but less than 250 mg kg^{-1}. Generally, this suggests that tubers were deficient in Ca content. A possible explanation for widespread deficiency in tuber Ca content is due to low soil exchangeable Ca. Research has shown that tubers that are low in Ca concentration are predisposed to bruising during harvesting, handling and storage (Karlsson and Palta 2006).

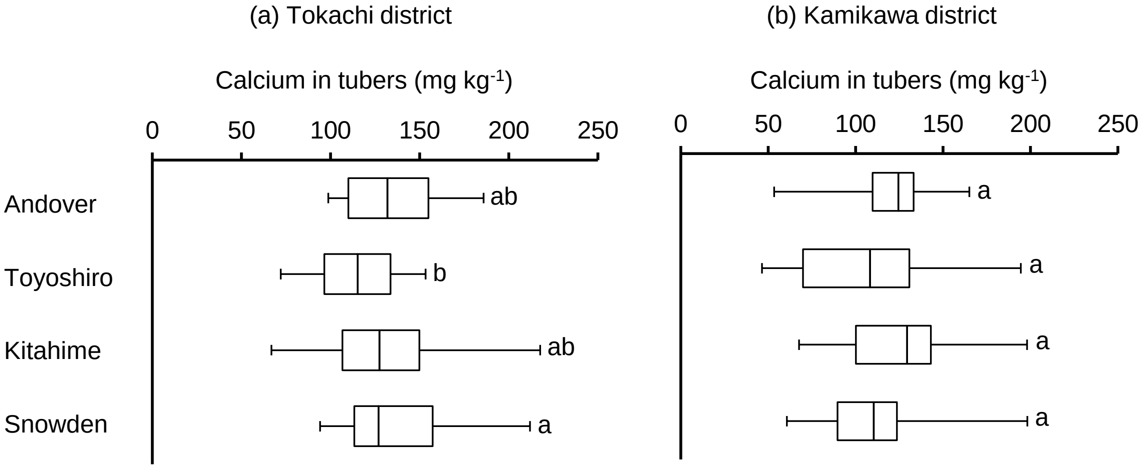


Figure 5.6. Box plots describing calcium concentration in tubers in four potato processing cultivars grown in 2013 and 2014 growing seasons in Tokachi and Kamikawa districts. Different letters indicate significance difference at p <0.05 by Tukey HSD test.

5.4.3. Prospects for increasing tuber Ca and improvement in potato quality

To assess the soil-to-potato tuber transfer of Ca, the soil Ca content and tuber Ca concentration were assessed (Fig. 5.7). The results demonstrated significant positive relationships between both exchangeable and water soluble Ca to tuber Ca content. This suggested that by increasing soil exchangeable Ca, we can increase potato tuber Ca concentration.

Table 5.2. Significance of location, growing season, and cultivar effects on tuber Ca content, specific gravity, incidence of bruise, and tuber internal quality for the four processing potato cultivars grown in Tokachi and Kamikawa districts in 2013 and 2014 growing seasons.

	Tuber Ca content	Specific gravity	Incidence of bruise	Tuber intenal quality[a]
P-values				
Growing season x location x cultivar	**0.003**	0.624	**0.022**	0.635
Location x cultivar	0.158	**0.037**	**0.001**	0.102
Growing season x cultivar	0.777	0.370	**0.006**	0.338
Growing season x location	0.975	0.827	**0.040**	0.587
Cultivar	**0.004**	**<0.001**	0.201	**<0.001**
Location	**0.001**	0.403	0.997	0.819
Growing season	**<0.001**	0.487	0.058	0.196

[a] Tuber internal quality; incidence of hollow heart, internal brown spot and internal necrosis. Values of P in bold are significant ($p < 0.05$).

This finding is consistent with previous studies and supports the idea that exchangeable Ca can be used to predict tuber Ca levels or assess the need for Ca fertilization (Simmons and Kelling 1987). However, contrary to the present results, Gunter and Palta (2008) did not find any relationship between soil exchangeable Ca and tissue Ca concentration, suggested that soil exchangeable Ca should not be used to assess tuber Ca needs. The observed differences could be attributed to differences in time of soil sampling. Soil exchangeable Ca values used in the study of Gunter and Palta (2008) reflected observed values before fertilizer application. In our study, soil exchangeable Ca reflected residual values at flowering stage. The response of tuber Ca concentration to soil exchangeable Ca in the current research therefore, underlies the importance of applying Ca fertilizer to increase soil Ca level.

5.4.4. Relationships between blackspot bruise, specific gravity and tuber Ca content

Incidence of blackspot bruise in Tokachi district varied between 0 to 36 % for all cultivars. The highest incidence of bruise was found for Toyoshiro (mean = 15 %) followed by Andover (mean =

13 %), Kitahime (mean = 12 %), and Snowden (mean = 12 % Fig. 5.8a). For Kamikawa district, incidence of bruise varied between 0 to 50 % for all cultivars. The highest mean incidence of bruise was found for Kitahime (mean = 22 %) followed by Snowden (mean = 14 %), Toyoshiro (mean = 11 %), and Andover (mean = 7.9 %; Fig. 5.8b). Generally, we observed lower rates of incidence of bruise in our study compared to previous studies (Karlsson and Palta 2006).

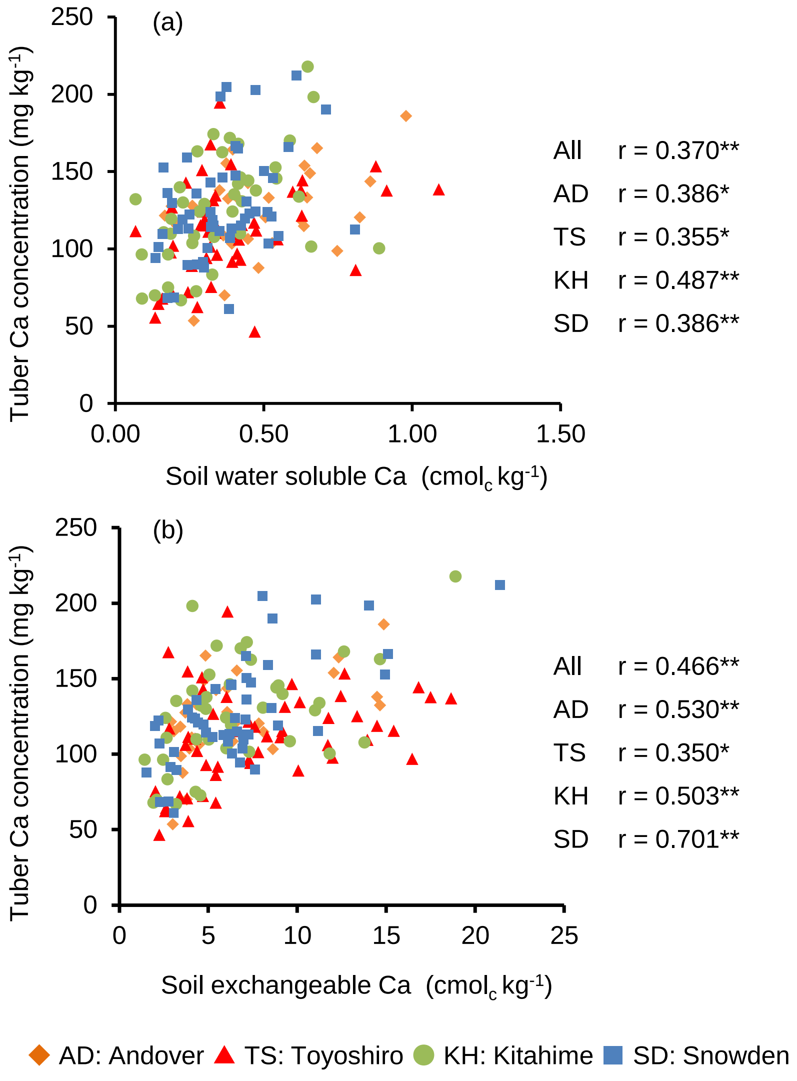


Figure 5.7. Relationships between (a) soil water soluble Ca and tuber Ca concentration, (b) soil exchangeable Ca and tuber Ca concentration of samples collected at flowering stage in 2013 and 2014 growing seasons (n = 170). r = Pearson correlation coefficient, *, ** indicate significant relationships between variables at $p < 0.05$ and $p < 0.01$, respectively.

The differences can be attributed to differences in cultivars, growing environments, and test methods.

We observed a wide variation in incidence of bruise within each cultivar that suggested that susceptibility of tubers to bruising was influenced by other factors. Previous reports demonstrated that blackspot bruise were directly related to specific gravity (Corsini et al. 1999), and data presented here supports these findings (Fig. 5.9a). Tubers with high specific gravity have high number of starch granules that increases potential of physical damage to cell membrane. Interactive effects of location, cultivar and growing season significantly affected bruise (Table 5.2). Performance of Snowden cultivar was significantly affected by location (data not shown) that may have caused interactive effects of location, cultivar and growing season on incidence of bruise.

Past research has shown a relationship between tuber Ca concentration and incidence of bruise (Karlsson and Palta 2006). In that work, the increase in tuber Ca from 100 to 250 mg kg^{-1} resulted in 50 % reduction in incidence of bruise. The overall trend of the data in the current study, showed a decrease in incidence of bruise with increase in tuber Ca concentration (Fig. 5.9b). Although this relationship was not statistically significant (data not shown), the trend suggests the possibility of lowering incidences of blackspot bruise by increasing tuber Ca concentration. The exact mechanism by which tuber Ca is able to reduce incidence of bruise is not clearly known. A number of hypotheses have been put forth to explain the mechanism of Ca in reducing susceptibility of

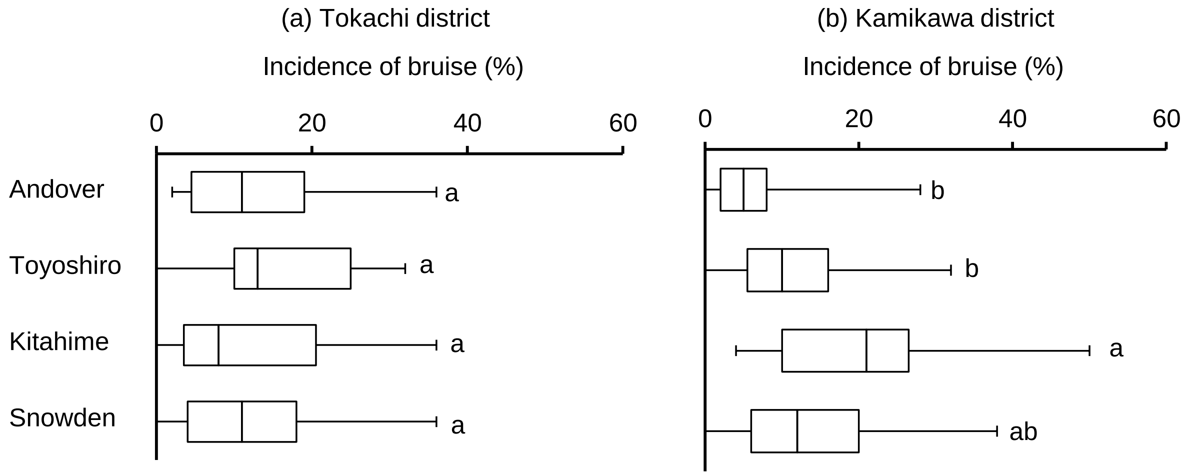


Figure. 5.8. Box plots describing incidence of blackspot bruise in four potato processing cultivars grown in 2013 and 2014 growing seasons in Tokachi and Kamikawa districts. Different letters indicate significance difference at p <0.05 by Tukey HSD test.

tubers to bruising. One such hypothesis is that Ca maintains cellular membrane integrity and strengthens cell wall. Blackspot bruise are caused by oxidation of phenols by PPO (Laerke et al. 2000). In non-bruised tubers, phenols and PPO are separated from each other by intercellular membrane that prevents discoloration of tuber tissues (Vaughn and Duke 1984). During bruising, mechanical impacts damages cellular membrane that allows phenols to come into contact with polyphenoloxidase leading to subsequent formation of the dark pigment (Corsin et al. 1992). Ca in tubers strengthens the structural properties of the membrane that enhances its resistance to physiological deterioration resulting from bruising impact. An alternative mechanism is that Ca regulates biochemical reactions that lead to melanin formation. Furthermore, Ca regulates the level of phenols (particularly tyrosine or phenolase) present in the tuber tissue (Mapson et al. 1963), and this lowers oxidative capacity of tuber tissues. As a secondary messenger, Ca controls cellular metabolism and functions of enzymes including PPO (Palta 1996). Low PPO levels in tubers limit its activity to react with phenols, and hence discoloration of tuber tissues.

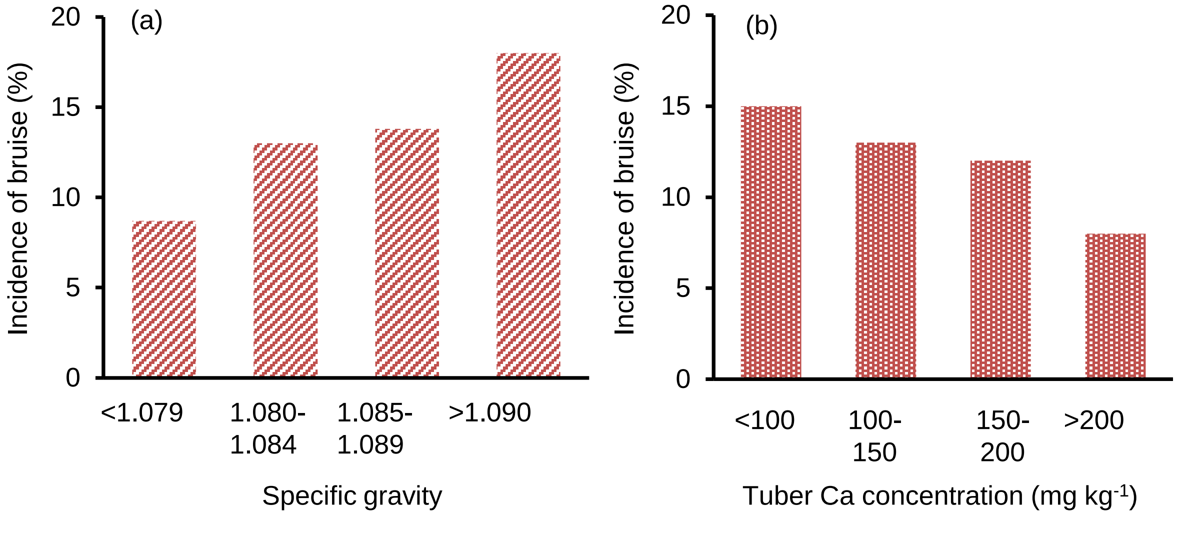


Figure 5.9. Relationships between (a) specific gravity and incidence of blackspot bruise, and (b) tuber Ca concentration and incidence of blackspot bruise of potato tubers collected in 2013 and 2014 growing seasons.

5.5. Summary

The results presented here demonstrate that soil Ca was deficient in 80% of the study fields in Hokkaido and none of the fields had tuber Ca concentration greater than 250 mg kg^{-1}, considered to mitigate incidence of blackspot bruise. There is evidence in our study that incidence of bruise can be mitigated by increasing tuber Ca concentration. Apparently, incidences of bruise were also influenced by specific gravity. The results show that tuber Ca concentration can be improved by increasing soil Ca levels. There is an urgent need to ameliorate soil Ca deficiency through application of Ca fertilizer.

CHAPTER 6. INFLUENCE OF SLOPE DIRECTION ON SOIL PROPERTIES AND POTATO YIELD POTENTIAL IN HILLY UPLAND FIELDS

6.1. Abstract

An understanding of the differences in yield potential and soil characteristics between slope directions in hilly uplands fields is fundamentally important for efficient management of the fields. Although the influence of topography or slope direction has been extensively studied, many of the studies focused on native or uncultivated lands such as forest ecosystems. The present study was done in hilly upland potato fields in Kamikawa district, Hokkaido, Japan to evaluate differences in yield potential and soil characteristics between slope directions. Eighty surface soil and potato samples were collected at flowering and harvesting stages, respectively, over a period of two years. Slope direction of each field was determined using ArcGIS software, and potato fields were categorized into two groups (North-facing and South-facing) based on slope direction. This study revealed that (1) the average soil total carbon was significantly higher in fields with north-facing slopes (18.5 g kg^{-1}) compared to south-facing fields (13.9 g kg^{-1}). In hilly upland fields, slope-facing slopes receives more solar radiation that increases surface soil temperature that in turn accelerated soil organic matter decomposition. (2) Cation exchange capacity was also significantly higher in north-facing compared to south-facing fields. (2) Tuber yields of Toyoshiro and Snowden cultivar were relatively higher in fields with slope direction facing south than those facing north. In conclusion, depending on the cultivar, potential yield may be influenced by both soil characteristics and slope orientation of the field.

Key words: Hilly upland fields, potato yields, soil properties, slope direction, solar radiation

6.2. Introduction

Soil organic matter (SOM) is a central component of soils that provide both nutrient and water holding capacity, reduce compaction, improve drainage and aeration, and enhance nutrient cycling and fertility, thereby increasing crop productivity and resource use efficiency in agroecosystems (Lal, 2004). In addition to providing important functions for crop production, SOM is also important environmentally as a sink for sequestering atmospheric CO_2 as well as reducing other greenhouse gas emissions including methane and nitrous oxide (Paustian et al., 2016). In arable fields, SOM can be lost by interactive effects of soil management such as intensive tillage, excessive inorganic fertilizer application, and minimum residue return (Hillel and Rosenzweig, 2011). Furthermore, surface cover is minimal in arable fields for prolonged periods of time, and receives both solar radiation and rainfall directly on bare soils. This can enhance the loss of SOM through higher decomposition rate by increased soil temperature as well as higher erosion rate by receiving high kinetic energy of rain.

Crop production on hilly upland fields is very common in many parts of the world. Topography creates variation in elevation, slope gradient, and slope direction (aspect; Tsui et al. 2004) that can cause higher erosion risks. In addition, the amount of solar radiation on a given location can be significantly altered in hilly upland fields. In northern hemisphere, it is well known that south facing slopes receive more solar radiation compared to north facing slopes (Auslander et al. 2003; Weil and Brady 2016). This is because sunlight rays in south facing slope strike the soil surface at a more direct angle leading to more solar radiation being concentrated on a small area. The angle at which the sunlight rays reaches the earth's surface determines how concentrated its energy is over that part of the earth's surface (Weil and Brady 2016).

Although the influences of slope direction on SOM have not been widely studied in arable land, there are extensive reports in native or uncultivated land covered with forest (Saremi et al. 2014; Maren et al. 2015; Lozano-Garcia et al. 2016; Qin et al. 2016). For example, Maren et al. (2015) found a difference in soil C stock and soil properties of north and south facing slopes whereby topographical factors affecting radiation and soil moisture content (Maren et al. 2015). Qin et al. (2016) also found a lower soil temperature and higher soil water content on northwest slope compared to south and southwest slopes in Qilian mountains in China. Amount of incoming solar radiation influences surface soil temperature and water content (Matsunaka 2014). Although the influence of topography or slope direction has been extensively studied, many of the studies focused on native or uncultivated lands such as forest ecosystems. In addition, each study has focused on a limited number of sites that provide little information about the effects of topography on a regional scale.

In this study, we chose Biei town as a model site for identifying the potential impacts of topography on soil and yield variation in cultivated fields. The cultivated area of Biei is dominated by wavelike, undulating topography with uplands and lowlands where potato cultivation is traditionally done. Preliminary evidence indicates that potato is very sensitive to variation in the growing conditions with variation among cultivars (Po et al. 2010). Deguchi et al. (2016) attributed potato yield difference between Abashiri and Teshikaga in Hokkaido prefecture to differences in solar radiation.

Understanding differences in soil characteristics and associated crop yield between slope directions in hilly uplands fields is fundamentally important for efficient management of the fields. The objective of the study therefore, was to evaluate the effects of slopes direction on soil properties and potato yields.

6.3. Materials and methods

6.3.1. Study site

The study was done in Biei town, Kamikawa district, one of the major potato production areas in Hokkaido prefecture during 2013 and 2014 growing seasons. Biei town is located in the central area of Hokkaido surrounded by mountains, hills and highlands. To the eastern side lie Mt. Tokachi, an active volcano and Yubari mountains to the western side (Fig. 6.1a).

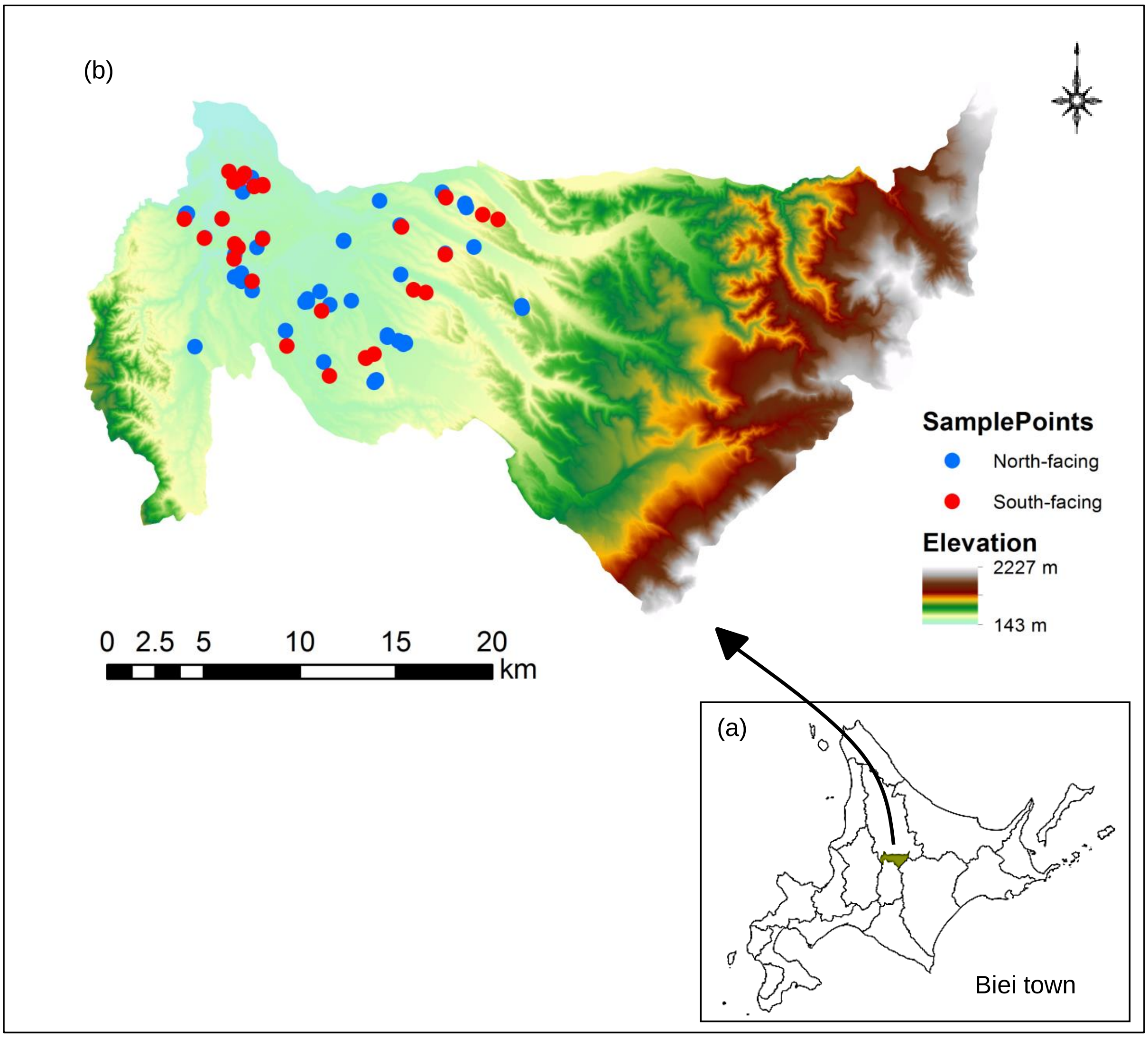


Figure 6.1. Maps of (a) Hokkaido showing Biei town, and (b) Biei town showing sampling sites (n = 80). Blue and red points indicates north-facing and south-facing fields, respectively.

The cultivated land in the region is dominated by wavelike hills and valleys formed from several pyroclastic flows from volcanic eruptions from Mt. Tokachi. The undulating topography with uplands rising to a height of 2227 m in mountainous area and 143 m in lowlands areas (Fig. 6.1b). Soils in the study region were developed from pyroclastic flow deposits and are classified as Upland soils (Cultivated Soil Classification Committee 1995) that are equivalent to Inceptisols, according to the Soil Taxonomy (Soil Survey Staff 2014).

6.3.2. Soil and potato tuber sampling

A total of 80 paired soil and potato tuber samples were collected at flowering and harvesting stages, respectively, to represent typical potato growing fields found in Biei town. Global position system (GPS) device was used to record the sampling locations. On each of the selected study field, representative sampling plot of 5-m row length was established where plant stand was relatively uniform (no missing plant). The size of each selected plot was three rows wide and 15 plants long, with a 75 cm between rows and 30 cm between plants. The sampling plot was placed at least 3 m away from the boundary and tractor paths to avoid border effects. Areas close to the ditches and manure dumps were avoided. As a result of the crop-rotation sequences, different potato study fields were used each year. Sugar beet (*Beta vulgaris* L.), winter wheat (*Triticum aestivum* L.), soybeans (*Glycine max* L.), and others preceded potatoes.

Soil samples were collected at flowering stage from two side rows. Ten sub-samples (5 samples from each row) were collected from 0-to-20 cm depth between the planting stations. The collected soil samples were thoroughly mixed and composited into one single soil sample for analysis. Potato tubers were harvested by hand from all 15 plants in middle row, and tuber more than 20 g were weighed to obtain yield per plot.

We also created two soil profiles at Hokuei (43°37’15.89” N, 142°27’14.92” E) and Omura (43°35’22.12”N, 142°25’07.25” E) in 2013 and 2017 respectively. The two sites were selected as typical soils found in Biei town.

6.3.3. Determination of slope direction

GPS data sets were analyzed using ArcGIS software (Arc Map version 10.31) with spatial analyst function. Topographic variables including slope gradient, elevation and slope direction were determined. Potato fields were categorized into two slope directions thus north-facing and south-facing slope, and two fields were on the flat land. Fields with slopes facing North West (270 to 360^{o}), north and North East (0 to 90^{o}) were grouped as north facing slope. While fields with slopes facing South East (90 to 180^{o}), South and South West (180 to 270^{o}) were grouped as south facing slope.

6.3.4. Soil analyses

Soil samples were air dried and passed through a 2-mm sieve before chemical analysis. The soil pH was measured with a glass electrode using 1:2.5 soil/water solution. Total carbon (TC) and total nitrogen (TN) contents were measured using a dry combustion method with a Vario EL III analyzer (Elementar Analysensysteme, Hanau, Germany). Acid-oxalate extractable aluminum (Alo) was determined using a 0.2-mol L^{-1} acid ammonium oxalate solution (pH 3) at a soil/solution ratio of 1:100 for 4 h equilibration in the dark (Blakemore et al. 1987), followed by measurement using the ICP-ES (ICPS-8100, Shimadzu Corporation, Kyoto, Japan). The cation exchange capacity (CEC) was measured by using ammonium acetate extraction method buffered at pH 7 as described by Schollenberger and Dreibelbis (1930). The Ca, Mg and concentration in the ammonium acetate extract was quantified by atomic absorption spectrophotometer (AAS; Z-5010, Hitachi Corporation, Tokyo, Japan). Phosphate absorption coefficient (PAC) was estimated based on the phosphate retained by the soil after equilibrium using a 2.5% diammonium phosphate solution, and measured by the colorimetric molybdate yellow method (Nanzyo 1997). PAC values determined by this procedure have been used extensively in Japan as an index of soil's capacity to make phosphate unavailable to crop. Available N was determined by hot water extraction method because it is the recommended method for routine evaluation for making N fertilizer recommendation in Hokkaido (Department of Agriculture, Hokkaido Government, 2015). For this analysis, N was measured by heating 1:10 soil/water solution in an autoclave at 105°C for one hour (Cutin et al. 2006), and N was quantified by total organic carbon analyzer (TOC-VCPH TNM-1, Shimadzu Corporation, Kyoto, Japan). Soil-available phosphate was estimated using the Truog method (Truog 1930). For this analysis, 0.5 mmol L^{-1} sulfuric acid (H_2SO_4) and ammonium sulfate ($(NH4)_2SO_4$) at pH 3 were used. The phosphate concentration in the filtrate was quantified by the colorimetric molybdate blue method developed by Murphy and Riley (1962).

Statistical analyses were carried out using Excel Statistics 2012 (Social Survey Research Information, Tokyo, Japan).

6.4. Results and discussion

6.4.1. Soil characteristics of the studied fields

Judging from surface soil assessment and other information including soil map and topography, we classified each field into its corresponding soil type. Using both Japanese (Cultivated Soil Classification Committee 1995) and Soil Taxonomy (Soil Survey Staff 2014), we found that 72 out of 80 fields were classified as Upland soils and only eight fields as Lowland soils that correspond to Inceptisols and Entisols, respectively. Lowland soils were generally found along the river banks or valleys and formed from alluvial deposits. Inceptisols were derived from pyroclastic flow deposits from Mt. Tokachi that is located in the eastern side of Biei town.

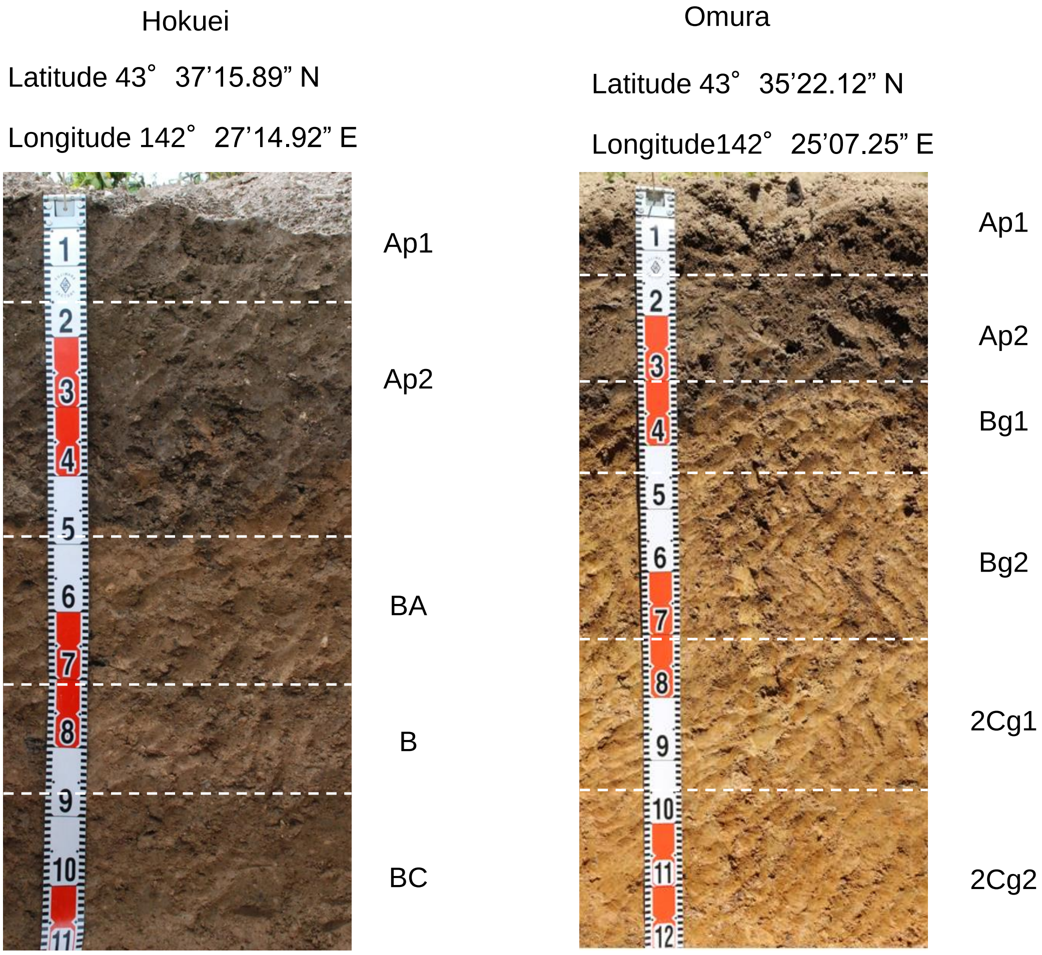
To understand the influence of volcanic activities on the soil charateristics, we checked if the soils met andic soil property criteria and also PAC values. We found that acid oxalate extractable Al + 1/2Fe < 2% (Table 6.1) and phosphate retention was less than 85%. Therefore, the soil failed to meet andic soil property criteria. Also, the average PAC value for all the data set in the current study was 740, which was lower than the threshold criteria of > 1500 used to distinguish Andosols from other soil types (Cultivated Soil Classification Committee 1995).

Table 6.1. Selected inherent soil chemical properties grouped based on slope direction.

Slope direction	pH (H_2O)	PAC[a]	Al_o[b] (g kg^{-1})	Alo + 1/2Fe_o[c] (%)
North-face	5.4 ± 0.37 a	790 ± 260 a	9.35 ± 3.6 a	1.43 ± 0.51 a
South-face	5.2 ± 0.30 a	620 ± 180 b	7.54 ± 2.3 b	1.21 ± 0.32 a
All dataset	5.3 ± 0.34 a	740 ± 250 ab	8.8 ± 3.4 ab	1.36 ± 0.46 a

[a]PAC; phosphate absorption coefficient. [b]Al_o; Al content extracted by acid oxalate. [c]Fe_o; Fe content extracted by acid oxalate. Values followed by different letters in a column are significantly different ($p < 0.05$).

Although on the eastern side of Biei town there is Mt. Tokachi, an active volcano that has had numerous eruptions in the past, the study area seemed not to be affected by the volcanic ash. Fujiwara et al. (2007) documented Mt. Tokachi volcanic eruptions of the past 3300 years, and reported that volcanic ash was only deposited on the eastern side of the mountain. It is not clear why all the past eruptions were deposited in eastern side and not in Biei town itself. In part, this could be related to direction of high altitude wind in Hokkaido. Past studies have shown that dispersal pattern of tephra during an eruptions was influenced by wind directions, violence of the volcanic eruption and type of volcanic ejecta (Shoji et al 1993). Westerly winds are common in Japan and influences the deposition of tephra. During volcanic eruption, materials brown in the air predominantly fall in the eastern side of the volcano because strong high altitude westerly winds blow from west to east (Shoji et al. 1993). This, in part, explains why soils from Biei town were not very much affected by the past volcanic ash depositions.



(a) Brown forest soil

(b) Gley upland soil

Figure 6.2. Photographs of common soils found in Kamikawa districts.

Table 6.2. Description of morphological properties of soil profiles of Hokuei and Omura sites in Kamikawa district.

Horizon	Depth (cm)	Moist soil color[a]	Mottling and concretion[b]	Field texture[c]	Soil structure[d]			Compactness[e]	Wetness[f]
Brown forest soil (Hokuei)									
Ap	0 - 15	10YR3/3	N	L	W	M	GR	L	MM
Ap2	15 - 40/48	10YR3/3	N	CL	W	F/M	SB	M	MM
BA	40/48 - 71	10YR4/6	N	CL	W	F/M	SB	L	MM
B	71 - 87	10YR5/6	N	CL	W/Mo	F/M	SB	L	MM/M
BC	87 - 106+	10YR5/6	N	CL	W/Mo	F/M	SB	L	MM/M
Gley upland soil (Omura)									
Ap1	0 - 14	10YR4/4	N	CL	W/Mo	M/F	GR/SB	L	MM
Ap2	14 - 33	10YR4/3	DI TU FeM FE	CL	W	VF/F	SB	M	MD
Bg1	33 - 48	10YR5/6	DI TU FeM FE	CL	W/Mo	F	SB	C	MM
Bg2	48 - 73	10YR4/6	FA CL FeM MA MnC FE	CL	W/Mo	VF/F	SB	VC	MM
2Cg1	73 - 98	10YR5/6	FA CL FeM AB	LiC	W/Mo	F	SB	C	MM
2Cg2	98 - 105+	7.5YR5/6	FA CL FeM AB MnC FE	LiC	W/Mo	F	SB	C	MM

[a] Based on Munsell color chart. [b] N, none; DI, distinct; TU, tubular; FeM, Fe mottling; FE, few; FA, faint; CL, cloudy; MnC, Mn concretions; MA, many; AB, abundant. [c] L, loam; CL, clay loam; LiC, light clay. [d] W, weak; Mo, moderate; VF, very fine; F, fine; M, medium; GR, granular; SB, subangular blocky. [e] L, loose; M, medium; C, compact; VC, very compact. [f] MD, moderately dry; MM, moderately moist; M, moist.

To confirm our surface soil assessment results, we also conducted in situ soil profile assessment and described them based on the Soil Survey Handbook (Japanese Society of Pedology 199) and also collected soil samples for physico-chemical analysis. Based on the results, the profiles were classified as brown forest soils (Fig. 6.2a) and gley upland soils (Fig.6.2b) that corresponded to Typic Dystrudepts and Typic Epiaquepts, respectively. The major differences between the two soil types are drainage and soil texture. Brown forest soils that are commonly found in mountainous and hilly areas were characterized by thick A black horizon, brown B horizon, and a clear boundary between A and B horizon (Fig. 6.2a). The pedon has low base saturation (<50%) and acidic in reaction as described by Obara et al. (2015). All horizon show a 10YR hue (Table 6.2). On the other hand, a gley upland soil (Typic Epiaquepts) was characterized by redoximorphic features and hydric conditions in the lower horizons (Fig. 6.2b). The profile showed reddish oxidized Fe and Mn concretions (mottles) in Bg1, Bg2, 2Cg1 and 2Cg2 horizons (Fig. 6.2b and Table 6.2) that suggested poor drainage. Soil texture and compaction as well as topographic position could be the main factors controlling water conditions in gley upland soils. Oxidized Fe coatings on roots and root channels could have been caused by oxygen transported into the soil. The soil compaction in the lower horizons thus Bg2 and 2Cg1 horizons (Table 6.1) caused what is described by Soil Survey Staff (2014) as perched water table or episaturation on top of relatively impermeable soil layer. In addition, high clay content in deeper horizons affected movement of water from top to bottom profiles.

6.4.2. Slope direction and soil characteristics

The study area was characterized by marked topographic variations with the elevation ranging from 143 m in the valleys to 2227 m a.s.l in mountainous region (Fig. 6.3a). However, the samples were collected from the cultivated land that lies between 226 to 449 m a.s.l. The slope directions and slope gradients are shown in figure 6.1. Using ArcGIS software, we found that 49 and 29 fields had north facing and south facing slopes (Fig. 6.3b), respectively. The average elevation for north facing fields was 319 m (ranged from 229 to 499 m) while south facing fields was 311 m (ranged from 226 to 473 m). Only two fields were on the flat land. The maximum slope gradient among the sampling sites was 30.1 % (Fig. 6.3a).

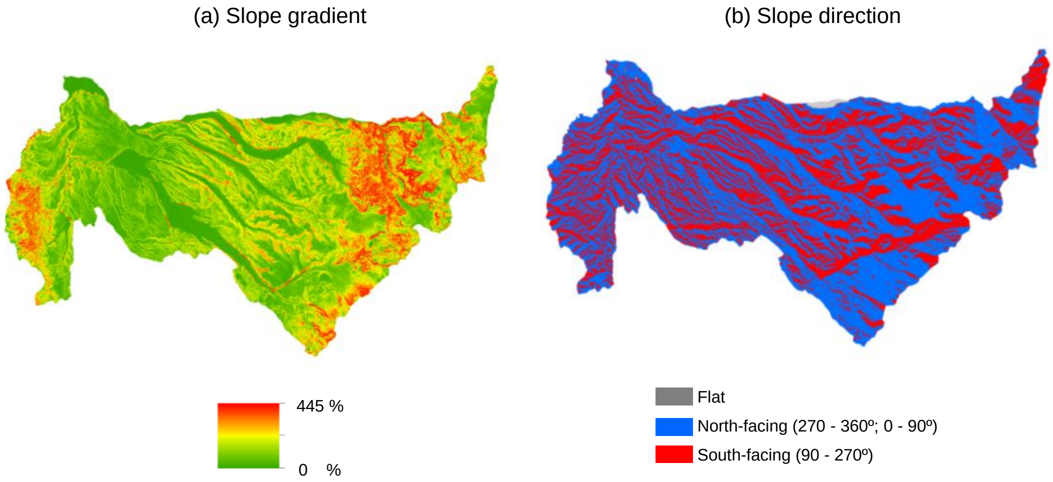


Figure 6.3. Maps of (a) slope gradient and (b) slope direction of Biei town.

The average slope gradient for North facing fields was 9.0 % (ranged from 0.5 to 30.1%) while south facing fields was 9.5% (ranged from 0.36 to 19.3%; Fig. 6.3a). Soil pH was slightly acidic in fields with south facing slopes compared to north facing fields (Table 6.1). However, TC was significantly higher in north facing fields (18.5 g kg^{-1}) compared to south facing fields (13.9 g kg^{-1}; Fig. 6.4a). While the exact mechanism causing differences in TC is not known, reports indicate that south facing slopes receives more solar radiation than north facing in northern hemisphere (Auslander 2003; Weil and Brady 2016). In theory, it is well known that solar radiation increases surface soil temperature (Matsunaka 2014; Weil and Brady 2016), although there had been a lack of field data to support this idea. We suggest that the increase solar radiation in south facing slopes increased surface soil temperature that accelerated both microbial activities and decomposition of SOM. The soils of the region are pyroclastic flow origin and contain high amount of quartz, which has low heat capacity relative to other soil constituents like SOM (Hillel, 1998). Also, if the precipitation between the two slope directions was constant, one would expect less evaporation in the north facing slope leading to high soil moisture content and low soil temperature. The current low SOM content of south facing slope suggests lower moisture holding capacity as well that can have lower moisture content to increase soil temperature. Increased soil temperature has been shown to result in increased SOM decomposition rates (Griffiths et al. 2009). In contrast to forest ecosystems, the arable fields have the soil bare for long periods of time.

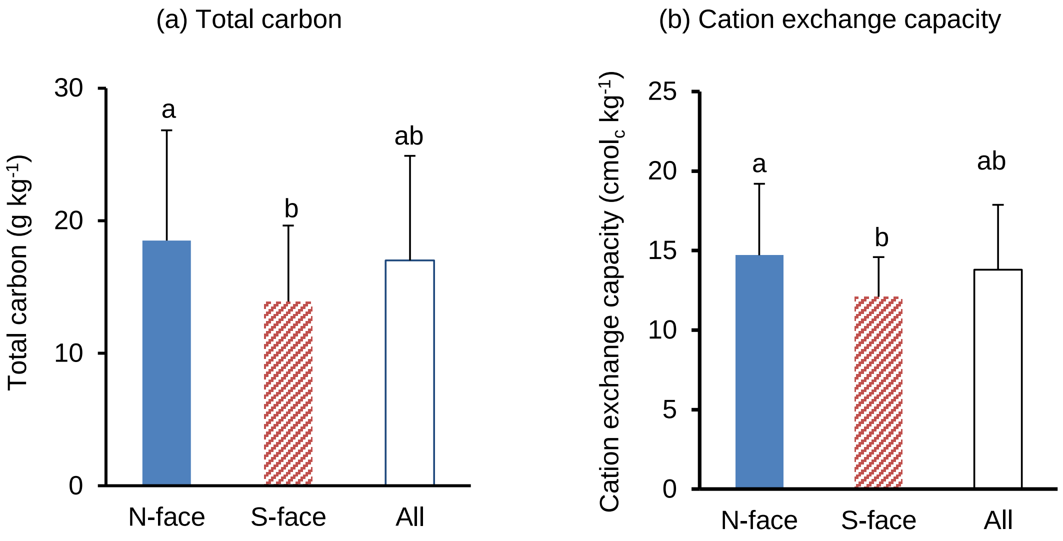


Figure 6.4. Mean comparisons of the grouped total carbon and cation exchange capacity based on slope direction. Different letters indicate no significant difference at 5% significance based on Tukey HSD test.

In Biei town and in surrounding area, crop rotation of potato, sugar beet, winter wheat, soybeans, and other vegetable crops. It is important to consider the amount of time when the soil is left bare in this cropping system because it can receive the effects of solar radiation as well as rainfall during this period of time. In the area, soils are covered with snow between December and March, and crops are planted starting in the end of April through to June apart from winter wheat. For any of the crops grown, the soils are left bare about four months of a year (Fig. 6.5). Also, the first one month after planting, the soils are only partially covered until the crops are fully grown. Therefore, the impacts of solar radiation and rainfall are thought to be much more pronounced in arable fields compared with forest ecosystems. Qin et al. (2016) reported lower soil temperature and higher soil water content in North West slope that received less solar radiation that reduced SOM decomposition compared to south facing slope. Variation in soil organic C caused by topography found lower soil temperature and higher water content on slope facing North West.

Difference in soil TC content affects functions of soils in each sampling site. CEC is a product of collective influence of organic matter content and clay mineral content and types. The differences in CEC in the current study could originate from differences in soil TC carbon (Fig. 6.4b). The average PAC values for north facing fields were 790 while south facing fields was 620 (Table 6.1).

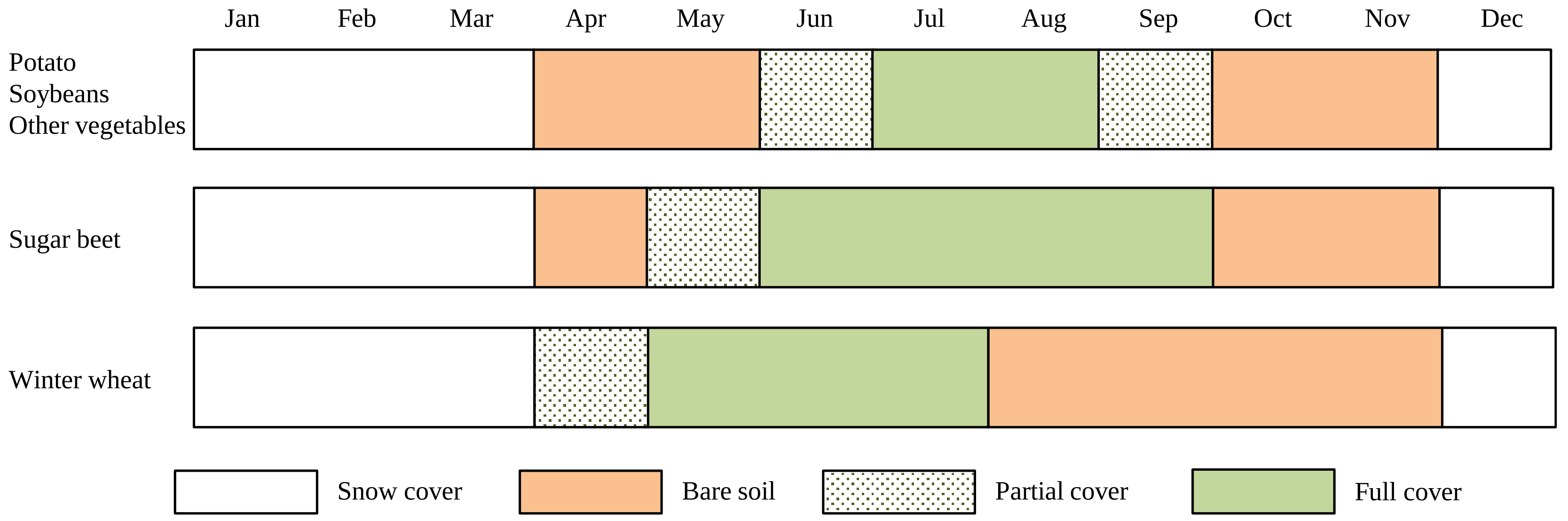


Figure 6.5. Crop seasons and soil cover in Kamikawa district, Hokkaido.

Although Al_o was significantly higher in north facing than south facing fields, $Al_o + 1/2Fe_o$ were almost the same (Table 6.1). The observed high PAC values in the north facing slopes could be related to Al_o and TC that increased specific surface area for phosphate retention. Amorphous materials have high surface are and are responsible for increased nutrient holding capacity (Mann et al. 2011). Higher Al_o content is an indicative of higher abundance of ligand exchange reaction sites for phosphate (Giesler et al. 2005). The measured Alo values are however low compared to our previous study on Andisols (Gondwe et al. 2017).

Hokkaido fertilizer recommendation has established recommended range of soil available nutrients to support crop growth (Hokkaido Government 2015). Generally, most fields have available soil nutrients higher than the established standard reference values (Chapter 2; Table 2.2). The data also showed no apparent difference in soil available N, P, and K between the two slope directions. Our previous research in the region has suggested that high soil available N, P, and K resulted from excessive in-season fertilizer application rates as described in chapter four.

Table 6.3. Soil available nutrients grouped based on slope direction.

Slope direction	N[a]	P	K	Ca
	(mg kg^{-1})	(mg P_2O_5 kg^{-1})	($cmol_c$ kg^{-1})	
North-face	47.5 ± 14.9 a	408 ± 138 a	0.691 ± 0.213 a	5.29 ± 3.390 a
South-face	47.4 ± 13.4 a	417 ± 143 a	0.803 ± 0.300 a	3.64 ± 1.410 b
All dataset	47.3 ± 17.7 a	409 ± 139 a	0.729 ± 0.253 a	4.68 ± 2.910 ab

[a]N; hot water extractable N. Values followed by different letters in a column are significantly different ($p < 0.05$)

Soil nutrients have been shown to be no longer limiting yield in potato production due to intensive nutrient management by growers (Gondwe et al. 2017).

6.4.3. Slope direction and potato tuber yields

Based on soil characteristics it would appear logical to think that north facing fields are the best and would give higher yields compared to south facing fields. This assumption was tested in this study by comparing yields of the four potato cultivars based on the slope directions.

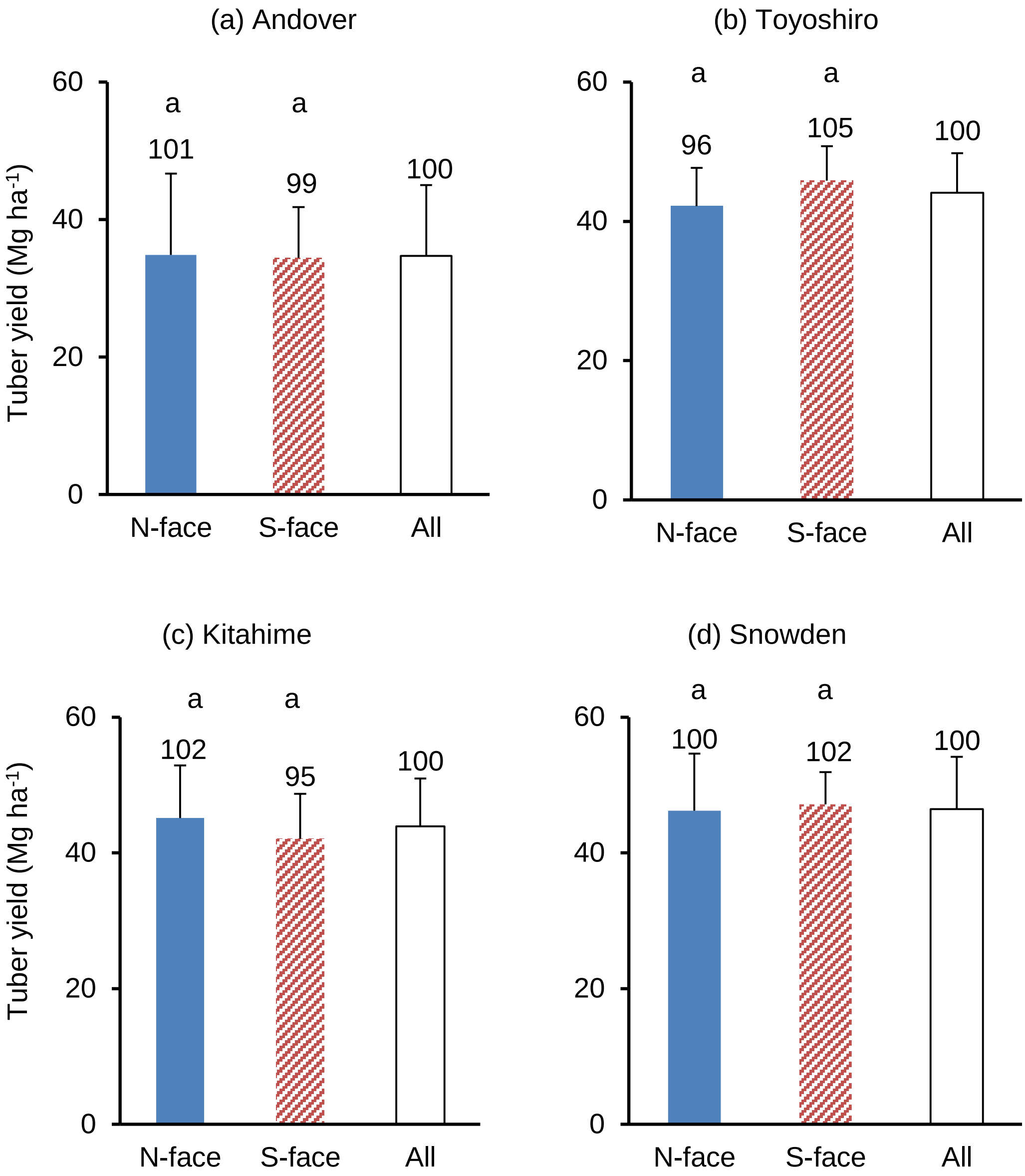


Figure 6.6. Mean comparisons of the grouped potato tuber yields based on slope direction. Values above the bars indicate percent values relative to the all data as 100%. Different letters letters indicate significant difference at 5% significance based on Tukey HSD test.

The results showed that Toyoshiro had higher yields in fields facing south compared to those facing north (Fig. 6.6b), although the difference was not statistically significant. According to the production ecology concept (van Ittersum and Rabbinge, 1997), crop yield is primarily determined by cumulative effects of CO_2 content, amount of solar radiation, temperature, and cultivar characteristics. These factors regulate physiological processes such as transpiration, photosynthesis, and respiration in a plant.

Subsequently, soil water and nutrients limit crop yields further (van Ittersum et al., 2013). In this study, Toyoshiro had higher yields in the south facing slope which suggests higher radiation amount and temperature caused higher yields. In contrast, Kitahime showed higher yields in fields facing north compared to those facing south. Kitahime cultivar was found to respond to soil conditions strongly as described in Chapter four. The tuber N, P, and K concentrations were strongly affected by soil available N, P, and K compared to other cultivars. The yields of Andover and Snowden cultivars were almost the same in both slope direction (Fig. 5a and 5d). We did not find other study reporting potato tuber yields difference with respect to slope direction in the literature. Although Persson (2005) did not find any association between slope direction and potato yield using C-association test in potato commercial fields of Canada, slope direction was not specified. In addition that study was done on limited number of sites that provided little information about the effects of topography. However, reports of corn and forage biomass are similar to our tuber yield findings. Afyuni et al. (1993) found soil properties, plant available water and slope direction have been shown to affect crop yields in different topography. Temperature is the main driving force for the production of potatoes. This suggests that yield may be influenced by in-coming solar radiation that accelerates the process of photosynthesis. In conclusion, some cultivars show higher crop yields in the south facing slope despite having lower soil TC and CEC. Other cultivars showed opposite trend where other growing conditions including soil factors affected the yield strongly. Depending on the cultivar, potential yield may be influenced by both soil characteristics and topography of the field differently. Potato production requires understanding yield liming factors to achieve consistently high yields.

6.5. Summary

Our study suggests that slope direction must not be excluded as a parameter that influences soil properties and crop yield. Potato tuber yield may be influenced by in-coming solar radiation that accelerates the process of photosynthesis. In conclusion, it is important to incorporate the topographical effects when we consider SOM dynamics both for agricultural production but for considering the environmental impacts.

Also, it is fundamental to consider factors that are known to determine yield potential before soil factors including solar radiation, temperature, and cultivar features when we conduct research into the relationship between soils and crop productivity.

CHAPTER 7. GENERAL DISCUSSION

7.1. Cultivar and soil types on yield components

In chapter 3, we confirmed that yield components among cultivars were different that reflected their inherent physiological differences. However, separation of individual cultivar yield components showed variations across soil types, and this variation was significant in stem number per plant. Stem number per plant were greater in the Kamikawa than Tokachi district. Because of the nature of our study, it was not possible to determine the exact mechanism causing the differences in stem number across the soil types. Previous studies have shown that apart from cultivar, yield components can also be influenced by other factors such as soil chemical properties, tuber seed size, tuber seed Ca content, and physiological age. Soil available phosphate, N, and exchangeable K were higher in Kamikawa compared to Tokachi fields but exchangeable and water soluble Ca were low. Maier et al. (2002) and Rosen and Bierman (2008) reported a significant increase in stem number per plant with P fertilization that was accompanied by increase in number of tubers per stem.

Another possible explanation for the interactive effects of soil type on stem number was differences in physiological age of potato seed piece used in the two growing seasons in Kamikawa district. Planting of potato was delayed by about two weeks in 2013 in Kamikawa district that may have increased the physiological age of seed tubers in that year. More stems per plant were observed in in 2013 compared to 2014. Past studies have shown that advanced seed-tuber age accelerates plant emergence, establishment, and decreases the dominance of apical growing point of tubers resulting in increased number of stems (Knowles and Knowles 2006).

Although stem number is one of the most important yield components in a potato crop, we observed no relationships with either total or marketable yields. Consistent with our study, Lynch et al. (2001) reported that stem number per unit area was a poor predictor of total and marketable yield and suggested to use tuber number per mainstem as a predictor for yield. In contrary, De la Morena et al. (1994) and Bussan et al. (2007) found that an increase in stem density was accompanied by increase in tuber yields. The disparity in yield response to stem density between the studies could be due to differences in statistical models used. While we assessed yield response to stem density using linear relationship, Morena et al. (1994) and Bussan et al. (2007) used path analysis and nonlinear regression model, respectively. Another possible explanation for the lack of response of tuber yield to stem density in the current study could be irregular plant spacing. We observed irregular intra-row spacing in the range of 19 to 42 cm apart while the regular intra-row spacing for potato in Hokkaido region is 30 cm that may have affected both plant and stem density.

Generally, increase in stem number per plant was associated with increase in tubers per plant because each stem is an independent production unit (Moorby 1978; Shayanowako et al. 2015). Increase in tuber number per plant was accompanied by an increase in number of undersized tubers as a result of inter-tuber competition for soil nutrients, moisture and light (Shayanowako et al. 2015). This underscores the importance of considering the number of stems per plant with regards to purpose for which the potato crop is grown. For chip processing, production goals require optimizing tuber sizes of specific size category to maximize finished product yield and profits for both growers and industry. In Hokkaido region, specific size requirement exists for chip processing cultivars, and marketable sized tubers range from 60 to 340 g (Murakami 2012). In USA, different pay scales exist according to tuber sizes across potato markets, and growers often receive premiums for tubers meeting specific size requirements (Bussan et al. 2007). Growers can optimize marketable yield by regulating number of stems per plant that in turn influences tuber size distribution. This can be achieved by using more juvenile potato seed tubers that produce less stems. Growers can also control stem number by planting high Ca content seed potato that have been shown to maintain sprout growth and prevent some changes attributed to physiological ageing (Dyson and Digby 1975).

7.2. Influence of soil type on yields and quality of processing potatoes

Although mean values of yields from individual fields were low, yields in some fields exceeded the attainable yields of major world potato producing countries. Potato yield varied from 21.9 to 68.2

Mg ha^{-1} indicating that with good crop management, there is a considerable yield-improvement opportunity. However, potato yield was cofounded by soil types and cultivar interactions effects, and the extent of yield variation of individual cultivar between soil types depended largely on cultivar. Yields of Toyoshiro, Kitahime and Snowden were not significantly different between Tokachi and Kamikawa districts, but that of Andover cultivar was 17% higher in Tokachi compared to Kamikawa district. This could be related to late planting of potatoes in 2013 in Kamikawa district that affected the yield of early maturing cultivars including Andover more than mid-season cultivars. Low temperature and sunlight hours in the spring of 2013 in Kamikawa district delayed planting of potatoes. Low temperatures early in the season delays canopy development, and reduce time available for tuber growth particularly in climate with short growing season (Yuan and Bland 2005) like Hokkaido.

Cultivar by soil type interaction effects were also observed on potato tuber specific gravity. While the performance of Andover, Toyoshiro, and Kitahime cultivar in terms of specific gravity was almost the same in the two soil types, specific gravity of Snowden was significantly higher in Kamikawa compared to Tokachi district. Surprisingly, separation of individual cultivar starch yield found that locally produced cultivars were less affected by the influence of soil type compared to imported cultivars. Starch yield for Andover was significantly higher in Tokachi compared to Kamikawa district whilst the performance Snowden cultivar was vice versa. The observed low starch content in Andover cultivar in Kamikawa district was expected because starch yield calculation is derived from specific gravity and yield, and Andover had low yield in Kamikawa district as discussed above. However, the observed low specific gravity and starch yield in Snowden cultivar in Tokachi district was not expected because the cultivar is an internationally known cultivar because of its high specific gravity and high tuber yield. This suggested that Snowden cultivar produces high specific when grown in Kamikawa compared to Tokachi district. Limitation of Snowden cultivar under the prevailing conditions of Tokachi soil types could be related to high availability of N as indicated in soil total carbon content (Table 3.1). Soil N availability and crop N uptake vary with soil type (Tremblay et al. 2012). High soil organic matter in Tokachi may have led to high soil N supply to crops as a result of organic N mineralization. Supply of more than optimal N to tubers particularly during late potato bulking period, stimulates vegetative growth and reduces available dry matter for tubers (Laboski and Kelling 2007). Moreover, growing late season cultivars such as Snowden in Hokkaido, is limited because of its long growing period. Hokkaido has a short growing season, and in the crop rotation, potato precedes winter wheat that is planted in Autum (from mid-september to late October). Inclusion of late season cultivars such as Snowden in crop rotation does not provide growers enough time window for seeding of winter wheat. Growers prefer short season cultivars like Andover because it allows farmers to have sufficient time for preparation of fields for the next crop (often winter wheat).

It is noteworthy that Toyoshiro cultivar showed not only good performance in terms of specific gravity but also produced consistent yield across the soil types. This explains the reasons that contribute to the continuing popularity of Toyoshiro cultivar in Japan. Growers therefore, need to carefully select cultivars adapted to a given locality to maximize both marketable yield and quality. This information is important to breeders, physiologists and agronomists who are interested in improving performance of potato crop.

7.3. Soil and in-season NPK fertilization on tuber yield quality and tuber composition

In chapter 4, we found that regardless of excess soil available NPK concentrations, growers were applying more than standard rates recommended by Hokkaido Fertilizer Recommendations. The gap between the recommended and growers rates was significantly larger in Kamikawa than Tokachi fields. Potato compared to other crops is generally perceived as having high response to NPK fertilizers due to its low nutrient efficiency and naturally shallow and poor developed root system (Iwama 2008; Sharma et al. 2017). This has justified large inputs of fertilizers even on soils with large amounts of available N, P, and K nutrients. However, in the current study, we found no yield response to soil available nutrients and in-season N, P and K fertilizer application rates that suggested that N, P, and K were not yield limiting factors. Similar to our findings, a large number of studies did not find any yield response to added NPK fertilizer in soils with varying amount of soil available NPK (Allison et al. 2001a; AbdeGadir 2003; Belanger et al. 2002; Hochmuth et al. 2002; Kang et al. 2014). This could be related to Hopkins et al (2018) report that there is a diminishing response of crop yield to increasing rates of fertilizers with an eventual plateau of no added response. Generally, our results suggested that under high soil available NPK, addition of NPK fertilizers does not increase yields. Abdalla et al. (1995) and Vos (1997) reported that excessive N fertilizer promotes vegetative growth that can delay tuber set and reduce tuberization leading to reduced yield. Similarly, Rosen et al. (2008) reported that phosphate fertilization reduced tuber size and increased tuber number, and had no effect on marketable yield. Sommerfeld and Knutson (1965) noted a reduction in yield in more than 50% of the cases where phosphate fertilizer rates exceeded the required amount. They suggested that the reduction in tubers yields was a result of the excessive use of phosphate fertilizer that reduced the tuber size and hastened maturity. Excess application of NPK fertilizers without a yield response is therefore, unnecessary cost to the farmer and should be avoided to maximize their economic return.

Generally, high accumulation of soil NPK led to luxury absorption of the nutrients by the potato crop that did not translate into yields. We do not have an exact explanation as to why high available N, P, K in the soil was positively related to tuber N, P, and K concentration. Past studies have established that potato tuber and stolons have roots that transport Ca from the surrounding soil solution to the tuber independent of the plant. We don’t know whether N, P, and K are also in part taken up by tubers independent of the plant, future studies should focus on understanding the possibility of tuber roots to also absorb N, P, and K from the soil solution and transport to the tuber. So far, it is believed that most plant nutrients including N, P and K in potato plant moves from shoot to tubers during growth, final bulking stage, and during canopy senescing.

Tuber N and K concentration was strongly associated with low specific gravity. This finding corroborated past studies that concluded that the effects of N on specific gravity appeared to be a major factor when fertilizer rates exceeded the needs of a plant. The observed trend in specific gravity with increase in tuber N could be attributed to N stimulating excess vine growth more than tuber growth that resulted in low dry matter concentration. Alternatively, N is associated with Gibberellin biosynthesis, and high Gibberellin levels inhibit tuberization (Abdalla et al. 1995) and impede accumulation of starch in tubers (Vreugdenhil and Sergeeva 1999). Although K is required for sugar translocation and starch synthesis, high concentration of K in tubers promotes water accumulation resulting in decreased specific gravity (Westermann 2005; Kumar et al. 2007). Studies have suggested that 18 g kg^{-1} of tuber K concentration may result in optimum quantity of dry matter for chip processing potatoes (Westermann and Tindall 2000). In the current study, 86% of the fields had tuber K concentration exceeding 18 g kg^{-1}. This increased the risks of reducing tuber quality for chip processing.

Interestingly tuber P concentration was not related to specific gravity except in the cultivar Toyoshiro where there was a negative relationship. Studies on the evaluation of the effects of P fertilizer rates on specific gravity have shown variable results. Addition of P fertilizer on soils testing low in available P has been shown to increase total solids and dry matter content because P is required for synthesis and storage of starch in tubers (Houghland 1960; Alvarez-Sanchez et al. 1999). However, under high availability of soil P, application of P fertilizer had nonsignificant effect on specific gravity (Rosen and Bierman 2008). Although P is important for phosphorylation of starch in tubers, excessive P is associated with faster closure of canopy and shorten the growing period (Sommerfeld and Knutson 1965; Sharma and Arora 1988).

It is noteworthy that in addition to influencing tuber yield and quality, excess NP fertilizer rates in non-responsive soils such as those of Tokachi and Kamikawa region poses a high risk of nonpoint pollution. Excess N input over output in an agroecosystem may lead to losses though volatization, denitrification, leaching and runoff that can cause air and water pollution (Vos 1997). Similarly, phosphate in dissolved form in runoff water or adsorbed form on eroded soil particles can cause water quality degradation in streams, rivers and lakes (Ruark et al. 2014). Therefore, farmers need to apply fertilizers based on recommendation to reduce the potential environmental degradation associated with excessive fertilization.

7.4. Soil and tuber calcium effects on potato tuber quality

In chapter 5, we found that over 80% of potato fields in Tokachi and Kamikawa district were severe deficient in soil Ca content. Growers avoid application of Ca containing fertilizers for fear of inducing development of common scab disease *Streptomyces scabies*. Although Goto (1985) suggested that increase in exchangeable Ca induced scab development, no other study has supported this interpretation. Lambert and Manzer (1991) tested this hypothesis by applying dolomitic lime equivalent to 960 kg Ca ha^{-1}, and observed no relationship between increases in soil exchangeable Ca and scab development.

Growers also believe that Ca containing fertilizer increases soil pH that is associated with development of common scab. Common scab causing pathogen, such as *Streptomyces scabies*, is perceived to be sensitive to soil pH, and have an optimal pH range for its activity and infection of potato tubers. Maintaining soil pH out of common scab tolerance range is recognized as an effective way of suppressing the disease (Lacey and Wilson 2001). However, a detailed study on the relationship between soil pH and the severity of common scab revealed that soil pH is not the direct cause of the disease (Mizuno and Yoshida 1993). The study showed that the effect of soil pH on development of common scab disease was an indirect effect of exchangeable Al. They demonstrated that at soil pH 5.3, it was possible to suppress common scab with exchangeable acidity Y_1 between 7 and 8, however, at similar pH and exchangeable acidity Y_1 between 3 and 4, decreasing soil pH did not suppress common scab. Al becomes available at low pH and causes toxicity problems if exchangeable Al is high in the soil solution. Exchangeable Al greater than 2 $cmol_c\ kg^{-1}$ is considered to be high enough to affect plant growth in Andisols (Saigusa et al. 1980). In the current study, no sample had exchangeable Al greater than 2 $cmol_c\ kg^{-1}$. This could be bacause Andisols are dominated by non-exchangeable Al species that are not easily displaced even at low pH. Surprisingly, even Inceptisols and Entisols showed low Y_1 in the current study. The Entisols of Tokachi could be affected by volcanic ash whereas all soils in Kamikawa had not been influenced by volcanic ash. Therefore, the concept of using low pH levels to control common scab appeared not be effective in all soils collected in this study.

Evaluation of tuber Ca content found that generally, all tuber samples had Ca values lower than the reported value (250 mg kg^{-1}) considered to mitigate incidence of bruise. A possible explanation for widespread deficiency in tuber Ca content was due to low soil Ca level. It is noteworthy that we also observed cultivar and soil type interaction in tuber Ca concentration. Although Hokkaido Fertilizer Recommendations uses Ca saturation to characterize plant available Ca (Department of Agriculture, Hokkaido Government 2015), soil exchangeable Ca was closely related to tuber Ca content. Soil exchangeable and water soluble Ca were higher in Tokachi compared to Kamikawa samples that corresponded with tuber Ca content. Four of the 170 samples that had tuber Ca concentration higher that 200 mg kg^{-1} came from Tokachi fields. This suggested that there is possibility to increase tuber Ca content by increasing water soluble and exchangeable Ca.

Assessment of susceptibility of tubers to bruising found that bruise incidence was influenced by both specific gravity and tuber Ca content. Tubers with high specific gravity were more susceptibility to bruising due to high starch granules that have been shown to increase the potential of physical damage to intra-cellular membrane (Corsin et al. 1999). On the contrary, high tuber Ca concentration reduced susceptibility of tubers to bruising, although the relationship was not statistically significant. This colloborated past studies that reported an increase in tuber Ca content from 100 to 250 mg kg^{-1} resulting in 50% reduction in the incidence of bruise (Karlsson et al. 2006). However, the exact mechanism by which tuber Ca was able to reduce incidence of bruise was not clearly known. A number of hypotheses have been put forth to explain the mechanism of Ca in reducing susceptibility of tubers to bruising. One such hypothesis is that Ca maintains cellular membrane integrity and strengthens cell wall. Blackspot bruise are caused by oxidation of phenols by polyphenol oxidase (PPO; Laerke et al. 2000). In non-bruised tubers, phenols and PPO are separated from each other by intercellular membrane that prevents discoloration of tuber tissues (Vaughn and Duke 1984). During bruising, mechanical impacts damages cellular membrane that allows phenols to come into contact with polyphenoloxidase leading to subsequent formation of the dark pigment (Corsin et al. 1992). Ca in tubers strengthens the structural properties of the membrane that enhances its resistance to physiological deterioration resulting from bruising impact.

An alternative mechanism is that Ca regulates biochemical reactions that lead to melanin formation. Furthermore, Ca regulates the level of phenols (particularly tyrosine or phenolase) present in the tuber tissue (Mapson et al. 1963), and this lowers oxidative capacity of tuber tissues. As a secondary messenger, Ca controls cellular metabolism and functions of enzymes including PPO (Palta 1996). Low PPO levels in tubers limit its activity to react with phenols, and hence discoloration of tuber tissues. Growers, therefore need to increase soil Ca levels by applying water soluble Ca.

7.5. Influence of slope direction on soil properties and potato yields

In chapter 6, we found that soils of north-facing slopes had significantly higher TC and CEC compared to soils of south-facing slopes. These are soil parameters serve as useful tools to assess the overall quality of cultivated soils and help to make inferences about the sustainability of current farming practices or land use pattern (Begum et al. 2010). Past studies have shown that south-facing slopes received more solar radiation than north-facing slopes in the northern hemisphere (Auslander et al. 2003; Weil and Brady 2016). Other studies have also shown that solar radiation increases surface soil temperature (Matsunaka 2014; Weil and Brady 2016), that in turn accelerates SOM decomposition rates (Griffiths et al. 2009). Therefore, the observed low SOM in south-facing fields could have resulted from increase in solar radiation that increased surface soil temperature that accelerated both microbial activities and decomposition of SOM. Moreover, soils of Kamikawa region are pyroclastic flow origin and contain high amount of quartz, which has low heat capacity relative to other soil constituents like SOM (Hillel, 1998). In contrast to forest ecosystems, the arable fields have the soil bare for long periods of time. In Biei town and in surrounding area, growers practice crop rotation of potato, sugar beet, winter wheat, soybeans, and other vegetable crops. It is important to consider the amount of time when the soil is left bare in this cropping system because it can receive the effects of solar radiation as well as rainfall during this period of time. In the area, soils are covered with snow between December and March, and crops are planted starting in the end of April through to June apart from winter wheat. For any of the crops grown, the soils are left bare about four months of a year. Also, the first one month after planting, the soils are only partially covered until the crops are fully grown, particularly potatoes emerge slowly following planting making the soil more susceptible to the effects of solar radiation. Therefore, the impacts of solar radiation and rainfall are thought to be much more pronounced in arable fields compared with forest ecosystems. Also, if the precipitation between the two slope directions was constant, one would expect less evaporation in the north facing slope leading to high soil moisture content and low soil temperature.

The differences in CEC in the current study could have originated from differences in soil TC carbon (Fig. 6.4). CEC is a product of collective influence of organic matter content and clay mineral content and types. North-facing slopes had significantly higher CEC compared to south-facing slope because of differences in TC as described above. Significant differences in Al_o between slope directions could be attributed to weathering process. Rech et al. (2001) found accelerated rates of weathering and soil development to occur in soils on south-facing slopes. In the same study, it was reported that the differences in soil development resulted from the amount of insolation received by the opposing slopes. Higher temperatures on south-facing slopes increased rates of chemical weathering on these aspects. High Al_o and TC in north-facing slopes increased specific surface area of the soil that was reflected in high PAC values in north- compared to south-facing slopes. Moreover, higher Al_o content is an indicative of abundance of ligand exchange reaction sites for phosphate (Giesler et al. 2005). Amorphous materials have high surface area that is responsible for increased nutrient holding capacity (Mann et al. 2011).

Exchangeable Ca was significantly higher in the north-facing compared to south-facing slopes because of its interaction with SOC (Table 6.3). Soil with high organic matter is known to specifically adsorb exchangeable Ca. A large number of studies summarized by Rowley et al. (2018) indicated that Ca^{2+} readily exchange its hydration shell and create inner sphere complexes with organic functional groups. Regardless of slope direction, most fields had available soil N, phosphate and exchangeable K higher than the established standard reference values in upland fields of Hokkaido (Department of Agriculture, Government of Hokkaido 2015). High accumulation of soil available N, P, and K was attributed to extrinsic factors particularly excessive in-season fertilizer management. Separation of soil available NPK data based on slope direction showed no significant difference (Table 4.3). Potato compared to other crops is generally perceived as having high response to NPK fertilizers due to its low nutrient efficiency and naturally shallow and poor developed root system (Iwama 2008; Sharma et al. 2017). This justifies large inputs of fertilizers even on soils with large amounts of available N, P, and K nutrients. Soil nutrients have been shown to be no longer limiting yield in potato production due to intensive nutrient management by growers as described in Chapter 4. In contrast, soil exchangeable Ca was lower than the recommended range (40 to 60% Ca saturation) by Hokkaido Fertilizer Recommendation (Department of Agriculture Hokkaido Government 2015) whilst exchangeable Mg was within the standard reference values. Growers in the region avoid application of Ca containing fertilizers in potato production in the belief that it causes potato scab disease (Chapter 5). Based on soil health indicators such as TC, CEC and base saturation, cultivated fields with north-facing aspect appeared to be more productive than south-facing slopes in northern hemisphere.

7.6. Slope direction and potato tuber yields

Although soil health indicators seemed to suggest that soils in north-facing slopes to be more productive than those of south facing slope, potato yield depended on cultivar. Toyoshiro had relatively higher yields in south-facing slopes compared to north-facing slopes while Snowden showed opposite trend. According to the production ecology concept (van Ittersum and Rabbinge, 1997), crop yield is primarily determined by cumulative effects of CO_2 content, amount of solar radiation, temperature, and cultivar characteristics. These factors regulate biological processes such as transpiration, photosynthesis, and respiration in a plant. Deguchi et al. (2016) compared actual and potential yields levels of potatoes in different production areas of Japan and concluded that potential yields were limited by the length of growing season and solar radiation. Therefore, higher yields of Toyoshiro cultivar in the south facing slope compared to north-facing slope suggested that the yield of Toyoshiro cultivar could be limited by solar radiation. In contrast, Kitahime showed higher yields in fields facing north compared to those facing south. Kitahime cultivar was found to have higher nutrient (N, P, and K) uptake efficiency compared to other cultivars (data not shown). Higher yields in north-facing slopes suggested that the cultivar was limited by soil available nutrients.

Depending on the cultivar, potato yield may be influenced by both soil characteristics and topography of the field differently. It is important to incorporate the topographical effects when we consider SOM dynamics for agricultural production and environmental impacts. Also, it is fundamental to consider primary factors that are known to determine yield potential before soil factors including solar radiation, temperature, and cultivar features when we conduct research into the relationship between soils and crop productivity.

CHAPTER 8. GENERAL CONCLUSIONS

(Towards improving yields and quality of processing potato in Hokkaido)

8.1. Performance of cultivars

Toyoshiro was the most suitable and best performing cultivar in terms of yield and quality characteristics for chip processing in both Andisols and Inceptisols compared to other cultivars. The good performance of Toyoshiro explains the reasons for its continuing popularity in Japan. Since growers and processors require stable yields and quality of potatoes in different environments, this information is important for growers to carefully select cultivars adapted to a given locality to maximize both yields and processing quality. This information may also be helpful to breeders to advance the breeding programs by using Toyoshiro cultivar as parents in breeding for both yields and processing quality.

8.2. Control stem number per plant to maximize marketable yields

Stem number per plant is an important consideration with regards to purpose for which the potato crop is grown because it has an implication on number and size of tubers produced. For seed growers, high number of stems per plant is desired in order to produce larger number of small size tubers. For commercial production such as chip processing, large size tubers are demanded by processing industry. In this connection, growers should regulate number of stems per plant to optimize marketable yields and crop value. This can be achieved by planting juvenile seed potatoes that have been shown to produce less number of stems. Alternatively, growers can plant high Ca content seed potato that has been shown to maintain sprout growth and prevent some changes attributed to physiological ageing.

8.3. NPK fertilizer best management practices

Excessive NPK fertilizer application did not increase yield while excess tuber NK concentration reduced specific gravity. Higher specific gravity tubers are desired for chip processing because more chips is produced per unit weight of tubers compared with tubers of lower specific gravity. In addition, there is a public concern about the need to reduce N in potato tubers following reports that high N concentration is associated with formation of acrylamide compound. Moreover, applications of NPK fertilizer above the recommended rates are unnecessary cost to the growers, and can raise potential environmental and human health concerns. Therefore, growers should optimize NPK fertilizer rates based on soil test results by following Hokkaido fertilizer recommendations to reduce the potential environmental degradation associated with excessive fertilization.

8.4. Increase soil Ca saturation levels

Soil Ca was deficient in about 80% of the study fields and none of the fields had tuber Ca concentration greater than 250 mg kg^{-1} (reported value to mitigate incidence of bruise). Incidence of bruise decreased with increase in tuber Ca concentration. However, there are prospects of increasing tuber Ca by increasing soil Ca levels. Water soluble and exchangeable soil Ca levels were strongly related to tuber Ca concentration. Growers need to increase both water and exchangeable soil Ca to improve potato quality. In short term, growers can increase water soluble Ca by applying readily soluble Ca fertilizers such as $CaSO_4$ and $Ca(NO_3)_2$ fertilizers. In long term, growers can increase exchangeable Ca by applying lime materials such as $CaCO_3$ to increase exchangeable Ca.

8.5. Site specific crop management

For precise management of crop production the spatial variability of crop and soil properties must be known. Knowledge of soil and crop variability is important for optimizing productivity and reducing environmental impacts. In hilly upland fields of Kamikawa district, slope direction creates potential for field variability. South-facing slope receives more solar radiation that increases surface soil temperature that in turn accelerates decomposition of SOM. Soil organic protection measures should consider slope direction and growers need to turn from general fertilizer recommendation to application based on soil test results to optimize productivity and reduce nutrient loss.

8.6. Yield potential influenced by soil properties and solar radiation

Potato yield in undulating landscapes Kamikawa district is influenced by the interaction of cultivar, soil types and slope direction. Depending on the cultivar, yield potential in hilly upland fields of Kamikawa may be influenced by among other factors soil properties and solar radiation. Since not all variation in yields were explained by soil properties, it is fundamental to consider primary factors that are known to determine yield potential before soil factors including solar radiation, temperature, and cultivar features when we conduct research into the relationship between soils and crop productivity. Future studies for the influence of slope direction on potato yield should focus on performance of cultivars on slope aspect.

CHAPTER 9. ABSTRACT

The consumption of processing potatoes is increasing in Japan, owing to change in eating habits from fresh potatoes to value added processed potatoes. Trends in potato production show that global potato production has been steadily increasing over the last 50 years partly as a result of increased use of fertilizers, fungicides, and irrigation. However, potato yield in Japan have been flattering since the 1990s and have not been meeting the required demand despite a lot of investments and expertise that goes in potato industry. Given the availability of suitable climate and soil conditions for potato production and consumer demand for processing potatoes, there is a desire for Japan to be self-sufficient in potato production. Within this framework, the goal of this study was to improve yield and quality of processing potato in Hokkaido, Japan. This goal was envisaged to be achieved through understanding the potato crop and soil-environmental factors that currently limit yields that can guide formulation of better management practices to improve productivity. To understand the quality characteristics of potatoes, the study assessed the status and relationships of soil N, P, K and Ca content and concentration of these nutrients in potato tuber as well as its influence on potato tuber processing quality. In hilly upland fields of Kamikawa, we also evaluated the influence of slope direction on soil properties and potato yields.

Paired soil and tuber samples were collected from 170 farmers' fields in Tokachi and Kamikawa districts in 2013 and 2014 growing seasons. The districts were purposely selected for the study because they are among the major potato producing areas in Hokkaido, accounting for almost 50% of the total production in Hokkaido. And also, the districts have contrasting soil types, Tokachi district is dominated by volcanic ash derived soils known as Andisols whilst Kamikawa district is dominated by soils of pyroclastic flow deposit origin classified as Inceptisols. Four chip processing potato cultivars thus Andover, Toyoshiro, Kitahime, and Snowden were selected for this study because they are among the most popular cultivars produced in Hokkaido region. The soil samples were collected at flowering stage while tuber samples were collected at harvest. For potato crop measurements, we determined individual weight of every tuber for calculation of yield

and specific gravity was measured by hydrometer. In order to understand the current growers' management strategies, we conducted interviews with all growers participating in the study.

Soil samples were analyzed for soil available nitrogen and phosphate, exchangeable calcium and potassium. Other soil properties were also assessed. Total carbon, phosphate absorption coefficient and acid oxalate extractable aluminum. We then dried and ground the potato samples, and wet digested the samples using sulfuric acid/hydrogen peroxide and quantified P, K, and Ca using inductively coupled plasma atomic emission spectroscopy (ICP-AES). While measurement of tuber N concentration was undertaken using a dry combustion method. ArcGIS software was used to determine slope direction and potato fields were grouped into north- and south-facing slopes based on their slope orientation.

In chapter 3, we found that Toyoshiro was the most suitable and best performing cultivar in terms of yield and quality characteristics for chip processing in both Andisols and Inceptisols compared to other cultivars. The good performance of Toyoshiro explains the reasons for its continuing popularity in Japan. Since growers and processors require stable yields and quality of potatoes in different environments, this information is important for growers to carefully select cultivars adapted to a given locality to maximize both yields and processing quality. The information of cultivar performance across location may be helpful to breeders to advance the breeding programs by using performing cultivars as parents in breeding for both yields and processing quality.

Stem number per plant is an important consideration with regards to purpose for which the potato crop is grown. For chip processing products, specific size category of tubers is demanded by processing industry. Generally, in this study, we found that increase in stem number was associated with an increase in tuber number per plant that in turn affected tuber size. Growers should regulate number of stems per plant to maximize marketable yields and crop value. This can be achieved by planting juvenile seed potatoes that are associated with less number of stems. Alternatively, growers can plant high Ca content seed potato that is associated with maintaining apical dominance of the sprout and prevent some changes attributed to physiological ageing.

In chapter 4, we found that excessive NPK fertilizer application did not increase yield while excess tuber NK concentration reduced specific gravity. The implication of this result was that under high soil available NPK, addition of NPK fertilizers does not increase yields and the observed lack of yield response was attributed to high availability of N, P, and K in the soil that obscured the relationship between yields and fertilizers. Generally, soil available N, P, and K led to luxury absorption of these nutrients by the potato crop that reduced specific gravity. For potato processing, high specific gravity tubers are desired for high quality potato chip products. Growers should optimize NPK fertilizer rates based on soil test results by following Hokkaido fertilizer recommendations.

In chapter 5, we found that soil Ca was deficient in about 80% of the study fields and none of the fields had tuber Ca concentration greater than 250 mg kg^{-1} (reported value to mitigate incidence of bruise). Incidence of bruise decreased with increase in tuber Ca concentration. There are prospects of increasing tuber Ca by increasing soil Ca levels. Water soluble and exchangeable soil Ca levels were strongly related to tuber Ca concentration. There is an urgent need to ameliorate soil Ca deficiency through application of Ca fertilizer. Growers need to increase both water and exchangeable soil Ca to improve potato quality. In short term, growers can increase water soluble Ca by applying readily soluble Ca fertilizers such as $CaSO_4$ and $Ca(NO_3)_2$ fertilizers. In long term, growers can increase exchangeable Ca by applying lime materials such as $CaCO_3$ to increase exchangeable Ca.

In chapter 6, we found differences in soil characteristics between north- and south facing slope that was caused by the amount of insolation received by the opposing slopes. Variation in the amount of solar radiation received created microclimatic differences that appeared to influence rates of chemical weathering and decomposition of SOM. It is important to incorporate the topographical effects when we consider SOM dynamics not only for agricultural production but also considering the environmental impacts. Although soil heath indicators seemed to suggest that soils in north-facing slopes to be more productive than those of south-facing slopes, potato yield between the opposing slopes depended on cultivar. This suggested that it is fundamental to consider factors that are known to determine yield potential before soil factors including solar radiation, temperature, and cultivar features when we conduct research into the relationship between soils and crop productivity.

In conclusion, soil and potato data collected from 170 farmers' fields presented a great wealth of information for studying potato growing environments. This study found that (1) Toyoshiro cultivar performed better than other cultivars in both Andisols and Inceptisols. (2) Increase in stem number was associated with an increase in tuber number per plant that in turn affected tuber size. Growers should regulate number of stems per plant to maximize marketable yields and crop value by planting juvenile and high Ca content seed potato (3) Excess NPK fertilizer application did not increase yield while excess tuber NK concentration reduced tuber quality. Growers should optimize NPK fertilizer rates based on soil test results following Hokkaido fertilizer recommendations. Application of NPK fertilizer above the recommended rates is unnecessary cost to the growers, and raise potential environmental and human health concerns. (4) Soil Ca was deficient in over 80% of the study fields in Hokkaido and none of the fields had tuber Ca greater than 250 mg kg^{-1}. Efforts are urgently needed to increase both water soluble and exchangeable Ca to improve the quality of potato quality by applying readily soluble Ca fertilizers and lime materials. (5) In hilly upland fields of Kamikawa district, south facing slopes creates potential for accelerated loss of SOM due to more insolation that increases surface soil temperature. Growers should consider site-specific management strategies to maximize crop yield and reduce risks of nutrient loss. Future studies are required to clarify the complex interactions between soil properties and slope direction on uncultivated soils.

Three-fold difference between the highest and lowest yield suggest a considerable yield-improvement opportunities if growers follow proper management practices. In this connection, we urge growers to follow best management practices recommended by Hokkaido Fertilizer Recommendation to maximize both yields and economic returns.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, Professor Masayuki Tani for the continuous support of my ph.D research and providing me with an excellent atmosphere for doing research. I could not have imagined having an excellent advisor and mentor of my ph.D study.

I wish to express my thanks to my co-advisors and thesis committee members: Dr. Daigo Aiuchi from Obihiro University and Professor Weiguo Cheng from Yamagata University for their insightful comments and encouragement, but also for the hard questions which motivated me to widen my research from various perspectives.

I would like to acknowledge the assistance of Dr. Rintaro Kinoshita for teaching and inspiring me how to write technical papers and also for willing to review my writings. Appreciation is also extended to Mr. Tsutomu Suminoe from Calbee Potato Company for his technical guidance and facilitating the selection of the study fields.

I am also thankful to Professor Jiwan Palta from University of Wisconsin-Madison for his expert and technical guidance that have been invaluable to my research and paper writing. I will live to remember his generosity and inspirational stories narrated to me about his student life and struggles that will always remain in my memory and motivate me to follow his footsteps and do my best to achieve great things in my career.

Special thanks should also go to all my laboratory members for their relentless support both morally and technically, and also to Dr. Sonam Sherpa from Cornell University for his constructive comments and pieces of advice that helped me to improve my thesis.

I am thankful to Calbee Potato Inc. and Obihiro University for funding this project, and to growers of Tokachi and Kamikawa districts for allowing us to use their fields. Finally, I am grateful to Japanese government for offering me the scholarship for both MSc and ph.D studies. I am honored to be one of the recipients of the prestigious Japanese government scholarship, MEXT.

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Appendix Table 1. Soil type, sample name, and cultivar for Tokachi district.

Year	Sample name	Soil type	Longitude	Latitude	Elevation (m)	Cultivar
2013	1-2-1	Andisols	N 42 48' 17.9"	E 143 06' 14.2"	130	Andover
2013	1-2-2	Andisols	N 42 47' 03.9"	E 143 07' 43.0"	131	Andover
2013	1-2-3	Andisols	N 42 46' 54.4"	E 143 01' 37.9"	198	Andover
2013	1-3-1	Andisols	N 42 46' 22.0"	E 143 05' 33.3"	155	Toyoshiro
2013	1-3-2	Andisols	N 42 45' 33.8"	E 143 03' 09.5"	198	Toyoshiro
2013	1-3-3	Andisols	N 42 46' 06.1"	E 143 07' 23.0"	145	Toyoshiro
2013	1-3-4	Andisols	N 42 45' 47.2"	E 143 04' 56.0"	166	Toyoshiro
2013	1-3-5	Andisols	N 42 51' 30.8"	E 143 03' 09.6"	158	Toyoshiro
2013	1-3-6	Andisols	N 42 49' 17.2"	E 143 09' 14.0"	108	Toyoshiro
2013	1-3-7	Andisols	N 42 49' 52.6"	E 143 06' 41.2"	130	Toyoshiro
2013	1-3-8	Andisols	N 42 46' 26.5"	E 143 02' 20.0"	200	Toyoshiro
2013	1-3-9	Andisols	N 42 45' 53.9"	E 143 02' 16.0"	203	Toyoshiro
2013	1-3-10	Andisols	N 42 46' 04.8"	E 142 59' 56.8"	227	Toyoshiro
2013	2-3-1	Andisols	N 42 53' 56.9"	E 143 00' 36.8"	105	Toyoshiro
2013	2-3-2	Andisols	N 42 52' 05.9"	E 143 00' 50.1"	129	Toyoshiro
2013	2-3-3	Andisols	N 42 52' 29.2"	E 143 03' 57.9"	112	Toyoshiro
2013	2-3-4	Andisols	N 42 54' 42.0"	E 143 05' 25.3"	82	Toyoshiro
2013	2-3-5	Andisols	N 42 56' 51.4"	E 143 04' 02.5"	123	Toyoshiro
2013	2-3-6	Andisols	N 42 57' 05.6"	E 143 03' 08.5"	108	Toyoshiro
2013	2-3-7	Andisols	N 42 52' 21.1"	E 142 59' 49.5"	160	Toyoshiro
2013	2-3-8	Andisols	N 42 47' 15.8"	E 142 58' 20.0"	235	Toyoshiro
2013	2-3-9	Andisols	N 42 47' 30.2"	E 143 00' 46.1"	195	Toyoshiro
2013	2-3-10	Andisols	N 42 56' 52.3"	E 143 01' 55.1"	97	Toyoshiro
2013	1-4-1	Andisols	N 42 44' 03.5"	E 143 06' 16.4"	165	Kitahime
2013	1-4-2	Andisols	N 42 50' 52.1"	E 143 07' 28.2"	119	Kitahime
2013	1-4-3	Andisols	N 42 47' 46.2"	E 143 04' 40.1"	152	Kitahime
2013	1-4-4	Andisols	N 42 47' 36.3"	E 143 03' 37.5"	169	Kitahime
2013	1-4-5	Andisols	N 42 46' 24.8"	E 143 03' 05.5"	187	Kitahime
2013	2-4-1	Andisols	N 42 56' 50.9"	E 143 03' 59.4"	99	Kitahime
2013	2-4-2	Andisols	N 42 52' 03.5"	E 142 57' 05.4"	196	Kitahime
2013	2-4-3	Andisols	N 42 43' 38.9"	E 143 00' 41.7"	258	Kitahime
2013	2-4-4	Andisols	N 42 51' 26.2"	E 143 05' 13.3"	105	Kitahime
2013	2-4-5	Entisols	N 42 58' 32.1"	E 143 02' 58.8"	198	Kitahime
2013	2-5-1	Entisols	N 42 53' 39.8"	E 143 02' 01.4"	97	Snowden
2013	2-5-2	Andisols	N 42 55' 05.3"	E 143 00' 18.5"	124	Snowden
2013	2-5-3	Andisols	N 42 52' 14.8"	E 143 04' 46.6"	103	Snowden
2013	2-5-4	Andisols	N 42 53' 35.1"	E 143 00' 29.4"	120	Snowden
2013	2-5-5	Andisols	N 42 48' 04.2"	E 142 58' 23.2"	217	Snowden
2013	2-5-6	Andisols	N 42 46' 57.2"	E 142 59' 56.4"	203	Snowden
2013	2-5-7	Andisols	N 42 47' 54.0"	E 143 02' 05.2"	162	Snowden
2013	2-5-8	Andisols	N 42 49' 51.3"	E 143 00' 45.2"	165	Snowden
2013	2-5-9	Andisols	N 42 51' 35.5	E 143 05' 43.9"	102	Snowden
2013	2-5-10	Andisols	N 42 56' 56.5"	E 143 01' 32.6"	108	Snowden
2013	1-5-1	Andisols	N 42 46' 39.9"	E 143 06' 12.4"	146	Snowden
2013	1-5-2	Andisols	N 42 45' 42.1"	E 143 03' 31.4"	188	Snowden

Appendix Table 2. Soil type, sample name, and cultivar for Tokachi district.

Year	Sample name	Soil type	Longitude	Latitude	Elevation (m)	Cultivar
2013	1-5-3	Andisols	N 42 46' 08.8"	E 143 07' 24.4"	142	Snowden
2013	1-5-4	Andisols	N 42 44' 43.4"	E 143 05' 28.7"	172	Snowden
2013	1-5-5	Andisols	N 42 40' 30.3"	E 143 03' 22.3"	270	Snowden
2013	1-5-6	Andisols	N 42 49' 46.2"	E 143 08' 44.0"	107	Snowden
2013	1-5-7	Andisols	N 42 50' 04.2"	E 143 06' 48.0"	120	Snowden
2013	1-5-8	Andisols	N 42 46' 58.3"	E 143 04' 27.2"	165	Snowden
2013	1-5-9	Andisols	N 42 46' 12.0"	E 143 00' 18.5"	225	Snowden
2013	1-5-10	Andisols	N 42 44' 01.1"	E 142 59' 58.7"	268	Snowden
2014	1-2-1	Entisols	N 42 48' 26.4"	E 143 06' 09.7"	131	Andover
2014	1-2-2	Andisols	N 42 47' 08.8"	E 143 06' 20.5"	141	Andover
2014	1-2-3	Andisols	N 42 47' 22.0"	E 143 02' 28.8"	174	Andover
2014	1-2-4	Entisols	N 42 48' 07.2"	E 143 07' 45.3"	122	Andover
2014	1-2-5	Andisols	N 42 47' 39.3"	E 143 07' 23.1"	127	Andover
2014	1-2-6	Andisols	N 42 46' 45.1"	E 143 05' 45.8"	150	Andover
2014	1-2-7	Andisols	N 42 46' 06.4"	E 143 03' 01.2"	187	Andover
2014	1-3-1	Andisols	N 42 50' 02.6"	E 143 06' 33.6"	117	Toyoshiro
2014	1-3-2	Andisols	N 42 49' 39.8"	E 143 08' 67.8"	114	Toyoshiro
2014	1-3-3	Entisols	N 42 45' 77.0"	E 143 03' 03.6"	193	Toyoshiro
2014	1-3-4	Entisols	N 42 45' 61.2"	E 143 04' 61.6"	177	Toyoshiro
2014	1-3-5	Entisols	N 42 46' 18.2"	E 142 59' 61.8"	213	Toyoshiro
2014	2-3-1	Andisols	N 42 57' 53.2"	E 143 01' 43.3"	100	Toyoshiro
2014	2-3-2	Andisols	N 42 53' 48.5"	E 143 07' 86.8"	90	Toyoshiro
2014	2-3-3	Andisols	N 42 51' 75.3"	E 143 04' 25.1"	123	Toyoshiro
2014	2-3-4	Andisols	N 42 52' 38.2"	E 142 59' 77.4"	157	Toyoshiro
2014	2-3-5	Andisols	N 42 58' 11.2"	E 143 04' 56.9"	153	Toyoshiro
2014	1-4-1	Entisols	N 42 44' 47.6"	E 143 06' 33.6"	157	Kitahime
2014	1-4-2	Andisols	N 42 50' 31.1"	E 143 08' 36.5"	101	Kitahime
2014	1-4-3	Andisols	N 42 46' 04.5"	E 143 04' 21.8"	168	Kitahime
2014	1-4-4	Andisols	N 42 47' 29.9"	E 143 07' 53.0"	155	Kitahime
2014	1-4-5	Andisols	N 42 46' 33.9"	E 143 02' 28.0"	189	Kitahime
2014	2-4-1	Entisols	N 42 56' 23.4"	E 143 02' 37.5"	71	Kitahime
2014	2-4-2	Andisols	N 42 53' 09.4"	E 142 57' 36.4"	176	Kitahime
2014	2-4-3	Andisols	N 42 44' 26.6"	E 143 00' 34.5"	241	Kitahime
2014	2-4-4	Entisols	N 42 51' 27.2"	E 143 05' 09.8"	113	Kitahime
2014	2-4-5	Andisols	N 42 58' 38.2"	E 143 02' 45.0"	169	Kitahime
2014	1-5-1	Andisols	N 42 46' 03.4"	E 143 01' 06.7"	204	Snowden
2014	1-5-2	Andisols	N 42 45' 03.1"	E 143 03' 24.2"	193	Snowden
2014	1-5-3	Entisols	N 42 46' 04.4"	E 143 07' 33.5"	135	Snowden
2014	1-5-4	Andisols	N 42 45' 15.3"	E 143 02' 04.1"	211	Snowden
2014	1-5-5	Entisols	N 42 49' 52.0"	E 143 07' 07.9"	100	Snowden
2014	2-5-1	Andisols	N 42 50' 58.4"	E 143 02' 45.0"	108	Snowden
2014	2-5-2	Andisols	N 42 53' 10.4"	E 143 00' 58.0"	126	Snowden
2014	2-5-3	Andisols	N 42 56' 56.7"	E 143 01' 37.5"	91	Snowden
2014	2-5-4	Andisols	N 42 49' 26.7"	E 143 00' 22.3"	179	Snowden
2014	2-5-5	Andisols	N 42 48' 01.3"	E 142 58' 20.8"	224	Snowden

Appendix Table 3. Slope direction, soil type, and cultivar for Kamikawa district.

Year	Sample name	Slope direction	Soil type	Longitude	Latitude	Elevation (m)	Cultivar
2013	3-2-1	North	Inceptisols	N 43 35' 01.6"	E 142 25' 21.9"	303	Andover
2013	3-2-2	North	Inceptisols	N 43 32' 59.1"	E 142 23' 32.3"	253	Andover
2013	3-2-3	South	Inceptisols	N 43 36' 01.7"	E 142 23' 58.7"	232	Andover
2013	3-2-4	North	Inceptisols	N 43 34' 11.5"	E 142 27' 53.9"	285	Andover
2013	3-2-5	North	Inceptisols	N 43 36' 42.6"	E 142 23' 16.0"	332	Andover
2013	3-2-6	North	Inceptisols	N 43 36' 43.4"	E 142 23' 19.8"	327	Andover
2013	3-2-7	North	Entisols	N 43 32' 57.8"	E 142 31' 36.0"	312	Andover
2013	3-2-8	North	Inceptisols	N 43 34' 54.9"	E 142 31' 31.8"	341	Andover
2013	3-2-9	South	Inceptisols	N 43 32' 57.3"	E 142 27' 05.2"	303	Andover
2013	3-2-10	North	Inceptisols	N 43 36' 52.4"	E 142 34' 03.9"	413	Andover
2013	3-3-1	North	Inceptisols	N 43 34' 55.0"	E 142 25' 13.1"	296	Toyoshiro
2013	3-3-2	North	Inceptisols	N 43 34' 47.6"	E 142 25' 22.9"	299	Toyoshiro
2013	3-3-3	North	Inceptisols	N 43 36' 02.6"	E 142 23' 59.4"	229	Toyoshiro
2013	3-3-4	North	Inceptisols	N 43 34' 05.9"	E 142 28' 46.6"	293	Toyoshiro
2013	3-3-5	South	Inceptisols	N 43 32' 40.8"	E 142 30' 26.8"	347	Toyoshiro
2013	3-3-6	South	Inceptisols	N 43 37' 27.5"	E 142 25' 55.9"	249	Toyoshiro
2013	3-3-7	North	Inceptisols	N 43 36' 43.7"	E 142 23' 19.1"	327	Toyoshiro
2013	3-3-8	Flat	Entisols	N 43 33' 00.6"	E 142 31' 21.1"	308	Toyoshiro
2013	3-3-9	South	Inceptisols	N 43 35' 27.2"	E 142 33' 16.1"	413	Toyoshiro
2013	3-3-10	North	Inceptisols	N 43 37' 12.4"	E 142 33' 11.1"	377	Toyoshiro
2013	3-4-1	North	Inceptisols	N 43 35' 45.0"	E 142 26' 00.0"	287	Kitahime
2013	3-4-2	North	Inceptisols	N 43 34' 11.7"	E 142 29' 35.7"	295	Kitahime
2013	3-4-3	South	Inceptisols	N 43 37' 28.4"	E 142 26' 16.2"	249	Kitahime
2013	3-4-4	South	Inceptisols	N 43 37' 49.3"	E 142 25' 34.0"	254	Kitahime
2013	3-4-5	North	Entisols	N 43 33' 02.4"	E 142 31' 23.6"	313	Kitahime
2013	3-4-6	South	Inceptisols	N 43 34' 28.5"	E 142 32' 01.4"	364	Kitahime
2013	3-4-7	North	Inceptisols	N 43 36' 17.5"	E 142 31' 32.5"	322	Kitahime
2013	3-4-8	North	Inceptisols	N 43 35' 28.8"	E 142 33' 15.9"	408	Kitahime
2013	3-4-9	South	Inceptisols	N 43 32' 06.1"	E 142 28' 42.7"	281	Kitahime
2013	3-4-10	North	Inceptisols	N 43 36' 45.2"	E 142 34' 06.7"	414	Kitahime
2013	3-5-1	Flat	Inceptisols	N 43 34' 47.6"	E 142 28' 17.7"	255	Snowden
2013	3-5-2	South	Inceptisols	N 43 35' 44.4"	E 142 25' 16.1"	260	Snowden
2013	3-5-3	North	Inceptisols	N 43 34' 10.9"	E 142 27' 48.7"	269	Snowden
2013	3-5-4	South	Inceptisols	N 43 37' 30.3"	E 142 26' 15.4"	253	Snowden
2013	3-5-5	North	Inceptisols	N 43 36' 44.1"	E 142 23' 18.6"	309	Snowden
2013	3-5-6	North	Inceptisols	N 43 35' 54.0"	E 142 29' 21.1"	294	Snowden
2013	3-5-7	North	Entisols	N 43 32' 57.2"	E 142 31' 34.9"	316	Snowden
2013	3-5-8	North	Inceptisols	N 43 36' 59.9"	E 142 30' 45.9"	317	Snowden
2013	3-5-9	North	Inceptisols	N 43 33' 23.3"	E 142 27' 02.9"	248	Snowden
2013	3-5-10	North	Inceptisols	N 43 36' 51.3"	E 142 34' 03.5"	409	Snowden

Appendix Table 4. Slope direction, soil type, and cultivar for Kamikawa district.

Year	Sample name	Slope direction	Soil type	Longitude	Latitude	Elevation (m)	Cultivar
2014	3-2-1	North	Inceptisols	N 43 32' 29.6"	E 142 28' 29.5"	302	Andover
2014	3-2-2	South	Inceptisols	N 43 34' 47.6"	E 142 25' 47.6"	294	Andover
2014	3-2-3	South	Inceptisols	N 43 35' 59.0"	E 142 26' 13.5"	287	Andover
2014	3-2-4	North	Inceptisols	N 43 34' 16.3"	E 142 27' 54.5"	274	Andover
2014	3-2-5	North	Inceptisols	N 43 36' 36.2"	E 142 23' 14.1"	318	Andover
2014	3-2-6	South	Inceptisols	N 43 35' 25.9"	E 142 25' 06.4"	252	Andover
2014	3-2-7	North	Entisols	N 43 32' 59.8"	E 142 31' 38.7"	309	Andover
2014	3-2-8	South	Inceptisols	N 43 34' 23.1"	E 142 32' 28.9"	395	Andover
2014	3-2-9	North	Inceptisols	N 43 31' 57.7"	E 142 30' 30.9"	368	Andover
2014	3-2-10	South	Inceptisols	N 43 36' 32.8"	E 142 34' 44.2"	443	Andover
2014	3-3-1	North	Inceptisols	N 43 34' 55.5"	E 142 25' 06.4"	288	Toyoshiro
2014	3-3-2	North	Inceptisols	N 43 34' 31.7"	E 142 25' 46.6"	293	Toyoshiro
2014	3-3-3	North	Inceptisols	N 43 36' 00.2"	E 142 26' 13.5"	292	Toyoshiro
2014	3-3-4	South	Inceptisols	N 43 33' 55.9"	E 142 28' 27.1"	299	Toyoshiro
2014	3-3-5	North	Inceptisols	N 43 37' 42.5"	E 142 25' 50.2"	255	Toyoshiro
2014	3-3-6	South	Inceptisols	N 43 37' 41.3"	E 142 25' 23.7"	226	Toyoshiro
2014	3-3-7	South	Inceptisols	N 43 32' 35.3"	E 142 30' 07.0"	330	Toyoshiro
2014	3-3-8	North	Entisols	N 43 33' 09.4"	E 142 30' 57.9"	298	Toyoshiro
2014	3-3-9	North	Inceptisols	N 43 35' 38.6"	E 142 34' 22.5"	328	Toyoshiro
2014	3-3-10	South	Inceptisols	N 43 36' 24.6"	E 142 35' 20.2"	473	Toyoshiro
2014	3-4-1	South	Inceptisols	N 43 36' 34.1"	E 142 24' 40.8"	284	Kitahime
2014	3-4-2	South	Inceptisols	N 43 37' 53.4"	E 142 24' 58.1"	244	Kitahime
2014	3-4-3	South	Inceptisols	N 43 37' 35.7"	E 142 25' 09.3"	249	Kitahime
2014	3-4-4	South	Inceptisols	N 43 36' 34.7"	E 142 23' 12.4"	332	Kitahime
2014	3-4-5	North	Entisols	N 43 33' 12.6"	E 142 30' 57.8"	300	Kitahime
2014	3-4-6	North	Inceptisols	N 43 31' 57.1"	E 142 30' 28.9"	374	Kitahime
2014	3-4-7	South	Inceptisols	N 43 36' 15.1"	E 142 31' 35.9"	329	Kitahime
2014	3-4-8	North	Inceptisols	N 43 33' 57.9"	E 142 36' 10.3"	499	Kitahime
2014	3-4-9	South	Inceptisols	N 43 32' 34.4"	E 142 30' 07.9"	331	Kitahime
2014	3-4-10	South	Inceptisols	N 43 37' 03.6"	E 142 33' 19.2"	377	Kitahime
2014	3-5-1	North	Inceptisols	N 43 34' 28.6"	E 142 28' 24.4"	267	Snowden
2014	3-5-2	South	Inceptisols	N 43 35' 51.1"	E 142 25' 08.6"	291	Snowden
2014	3-5-3	North	Inceptisols	N 43 34' 28.6"	E 142 28' 24.4"	265	Snowden
2014	3-5-4	North	Inceptisols	N 43 37' 18.3"	E 142 25' 28.4"	271	Snowden
2014	3-5-5	North	Inceptisols	N 43 35' 33.4"	E 142 25' 07.9"	274	Snowden
2014	3-5-6	North	Inceptisols	N 43 35' 52.4"	E 142 29' 20.8"	287	Snowden
2014	3-5-7	North	Entisols	N 43 32' 58.4"	E 142 31' 40.2"	314	Snowden
2014	3-5-8	North	Inceptisols	N 43 33' 53.9"	E 142 36' 11.8"	496	Snowden
2014	3-5-9	North	Inceptisols	N 43 31' 53.5"	E 142 30' 25.3"	371	Snowden
2014	3-5-10	South	Inceptisols	N 43 37' 02.5"	E 142 33' 20.0"	380	Snowden

Appendix Table 5. Physico-chemical properties of soil samples from Tokachi district.

Year	Sample name	pH(H_2O)	TC[a]	TN[b]	Oxalate[c]		PAC[d]	Exchangeable	
					Al	Fe		Al	Acidity
			(g kg^{-1})					cmol$_c$ kg^{-1}	(Y1)
2013	1-2-1	4.7	74.2	5.84	28.4	13.7	1980	0.07	2.6
2013	1-2-2	4.6	58.9	3.93	27.4	10.4	1750	0.08	2.2
2013	1-2-3	5.6	28.7	2.07	37.2	12.3	1720	0.00	0.7
2013	1-3-1	4.4	73.5	4.21	15.5	8.46	1560	0.32	4.1
2013	1-3-2	4.9	43.6	3.32	38.3	21.8	1770	0.02	0.9
2013	1-3-3	4.6	67.5	4.21	24.4	13.0	1800	0.13	3.3
2013	1-3-4	5.1	33.3	2.36	37.6	11.9	1690	0.01	0.7
2013	1-3-5	4.6	101	7.01	36.3	14.2	2260	0.12	2.8
2013	1-3-6	4.9	33.9	2.34	32.5	22.9	1500	0.03	0.9
2013	1-3-7	4.3	110	7.06	32.4	15.3	2260	0.65	5.9
2013	1-3-8	4.8	23.8	1.51	41.2	28.4	1860	0.05	1.3
2013	1-3-9	4.4	54.0	3.24	34.5	16.3	1980	0.41	4.0
2013	1-3-10	4.8	40.8	2.51	40.0	15.8	2010	0.05	1.5
2013	1-4-1	4.4	64.6	4.33	30.7	16.7	1950	0.53	4.6
2013	1-4-2	4.8	36.5	2.29	37.6	14.4	1950	0.04	1.0
2013	1-4-3	4.7	51.7	3.76	37.4	15.8	2030	0.12	2.3
2013	1-4-4	4.6	68.5	4.63	36.2	12.8	2100	0.14	2.4
2013	1-4-5	4.8	34.2	1.99	34.6	19.7	1790	0.03	1.1
2013	1-5-1	5.0	25.2	1.90	47.3	27.1	1930	0.01	0.7
2013	1-5-2	4.9	32.9	2.24	47.0	30.7	1980	0.04	0.7
2013	1-5-3	4.5	40.2	3.07	32.3	21.9	1700	0.17	3.4
2013	1-5-4	4.4	52.4	3.01	33.0	22.8	1900	0.39	4.2
2013	1-5-5	4.3	92.9	5.95	26.7	11.4	2100	0.91	7.2
2013	1-5-6	4.7	17.8	1.56	44.9	23.4	1770	0.05	1.4
2013	1-5-7	4.6	77.9	5.61	27.1	16.0	1950	0.13	3.2
2013	1-5-8	4.8	47.4	3.30	34.4	24.3	1790	0.06	1.5
2013	1-5-9	4.9	34.6	2.19	44.0	27.2	2040	0.04	1.3
2013	1-5-10	4.9	39.7	2.96	39.3	27.9	1920	0.04	1.2
2013	2-3-1	4.8	51.0	3.92	55.1	24.2	2240	0.08	1.9
2013	2-3-2	4.9	72.4	5.29	39.7	21.4	2080	0.05	2.1
2013	2-3-3	4.9	15.3	1.32	47.4	25.1	1740	0.03	1.2
2013	2-3-4	4.8	24.8	2.24	35.8	21.5	1740	0.06	1.5
2013	2-3-5	4.7	79.0	6.00	41.1	23.6	2150	0.10	2.3
2013	2-3-6	4.8	81.8	5.50	44.7	23.1	2230	0.09	1.7
2013	2-3-7	4.8	39.2	2.92	49.2	24.7	2180	0.09	1.8
2013	2-3-8	4.7	58.2	4.12	42.2	22.2	2020	0.16	2.5
2013	2-3-9	5.0	41.2	2.99	41.7	23.0	1850	0.05	1.7
2013	2-3-10	4.8	69.5	5.14	39.4	20.6	2050	0.08	2.2
2013	2-4-1	4.8	49.9	3.84	50.9	26.2	2130	0.08	2.0
2013	2-4-2	5.5	64.3	4.77	48.6	22.9	2110	0.00	1.2
2013	2-4-3	4.8	39.7	2.79	41.5	24.1	1940	0.09	2.9
2013	2-4-4	5.0	23.2	1.86	45.3	21.0	1810	0.02	1.2
2013	2-4-5	4.5	31.2	2.32	25.3	32.7	1450	0.16	2.8
2013	2-5-1	4.3	29.9	2.10	12.6	10.4	850	0.38	4.3
2013	2-5-2	4.7	101	6.35	29.0	11.0	2000	0.09	1.1

[a]TC; total carbon. [b]TN; total nitrogen, [c]Oxalate; acid oxalate extractable. [d]PAC; Phosphate absorption coefficient. .

Appendix Table 6. Physico-chemical properties of soil samples from Tokachi district.

Year	Sample name	pH(H_2O)	TC[a]	TN[b]	Oxalate[c]		PAC[d]	Exchangeable	
					Al	Fe		Al	Acidity
			(g kg^{-1})					cmol$_c$ kg^{-1}	(Y1)
2013	2-5-3	4.5	48.9	3.88	39.5	15.8	1830	0.30	4.0
2013	2-5-4	4.6	56.1	3.95	40.5	21.6	2040	0.15	2.5
2013	2-5-5	4.9	42.3	3.11	40.4	22.7	1810	0.05	1.6
2013	2-5-6	4.3	92.0	5.51	21.6	13.2	1850	0.89	6.7
2013	2-5-7	5.0	26.4	2.25	37.6	24.7	1620	0.03	1.1
2013	2-5-8	5.1	40.3	3.20	46.2	27.3	1940	0.02	1.4
2013	2-5-9	5.0	29.5	2.45	48.6	28.0	1800	0.02	1.2
2013	2-5-10	4.7	83.4	5.61	35.9	17.4	2050	0.13	1.8
2014	1-2-1	4.5	33.7	2.69	19.8	18.8	1200	0.17	2.8
2014	1-2-2	4.8	55.1	4.00	38.7	22.0	1740	0.09	1.3
2014	1-2-3	5.0	41.2	2.65	40.8	18.5	1800	0.04	0.7
2014	1-2-4	4.7	28.7	2.31	25.3	10.6	1180	0.09	2.6
2014	1-2-5	4.6	23.1	1.96	43.1	17.5	1780	0.19	2.7
2014	1-2-6	4.8	60.0	3.78	31.3	10.3	1660	0.08	1.5
2014	1-2-7	4.6	51.5	2.62	26.4	12.5	1700	0.25	2.9
2014	1-3-1	4.7	62.4	4.47	37.6	14.4	1800	0.08	1.3
2014	1-3-2	4.9	60.8	4.23	33.3	12.7	1590	0.02	0.7
2014	1-3-3	4.9	19.9	1.42	40.1	23.5	1480	0.02	0.4
2014	1-3-4	5.3	35.0	2.53	37.0	13.3	1460	0.00	0.0
2014	1-3-5	4.4	27.5	1.73	27.7	16.3	1390	0.30	2.1
2014	2-3-1	4.4	89.8	5.88	35.9	17.8	2000	0.31	4.0
2014	2-3-2	4.6	100	6.80	40.2	18.1	2110	0.14	2.1
2014	2-3-3	4.7	22.0	1.54	37.7	8.73	1570	0.06	0.7
2014	2-3-4	4.4	52.1	3.54	28.4	14.6	1610	0.23	2.9
2014	2-3-5	4.7	33.2	2.27	35.3	22.4	1650	0.03	0.7
2014	1-4-1	4.3	36.4	3.00	29.4	12.9	1400	0.45	3.7
2014	1-4-2	5.3	25.3	2.08	44.4	19.6	1640	0.00	0.0
2014	1-4-3	4.6	44.6	2.80	29.1	12.0	1560	0.12	1.3
2014	1-4-4	4.2	70.1	4.62	29.6	12.3	1780	0.24	2.9
2014	1-4-5	4.9	35.4	2.44	34.0	15.6	1480	0.01	0.7
2014	2-4-1	3.9	18.9	1.52	5.24	7.18	560	0.51	5.0
2014	2-4-2	5.2	48.5	3.72	46.6	11.9	1900	0.01	0.7
2014	2-4-3	4.6	33.5	2.09	31.4	8.32	1700	0.04	1.1
2014	2-4-4	4.4	17.9	1.46	39.8	12.9	1460	0.09	1.1
2014	2-4-5	4.7	60.1	4.30	31.9	13.5	1780	0.02	0.7
2014	1-5-1	4.4	69.9	3.77	24.2	7.57	1620	0.29	2.8
2014	1-5-2	4.7	33.7	2.55	35.3	7.97	1570	0.04	0.6
2014	1-5-3	4.6	32.7	2.38	20.6	8.79	1190	0.05	0.5
2014	1-5-4	4.9	35.3	2.54	36.0	12.3	1550	0.02	0.5
2014	1-5-5	4.2	74.0	4.79	16.3	13.8	1400	0.19	2.7
2014	2-5-1	3.9	76.2	5.16	27.7	15.4	1810	0.93	7.1
2014	2-5-2	4.8	52.7	4.01	47.8	19.8	1880	0.06	2.7
2014	2-5-3	4.1	59.5	4.25	26.3	12.6	1660	0.44	5.6
2014	2-5-4	4.4	61.3	4.36	43.1	12.6	1960	0.17	1.8
2014	2-5-5	4.7	49.9	3.61	25.6	8.58	1520	0.05	1.2

[a] TC; total carbon. [b] TN; total nitrogen, [c] Oxalate; acid oxalate extractable. [d] PAC; Phosphate absorption coefficient. .

Appendix Table 7. Physico-chemical properties of soil samples from Kamikawa district.

Year	Sample name	pH(H_2O)	TC[a]	TN[b]	Oxalate[c]		PAC[d]	Exchangeable	
					Al	Fe		Al	Acidity
			(g kg^{-1})					cmol$_c$ kg^{-1}	(Y1)
2013	3-2-1	4.3	21.4	1.75	9.54	9.29	850	0.51	6.6
2013	3-2-2	4.7	19.6	1.67	8.92	6.10	780	0.08	1.7
2013	3-2-3	4.4	15.5	1.41	8.98	21.0	780	0.34	4.4
2013	3-2-4	4.4	12.3	1.21	5.45	7.06	590	0.15	3.8
2013	3-2-5	4.3	12.9	1.15	4.39	7.63	420	0.14	2.9
2013	3-2-6	4.8	9.77	0.88	5.13	7.85	450	0.01	1.2
2013	3-2-7	5.2	36.7	3.01	16.2	21.9	1260	0.01	0.2
2013	3-2-8	4.3	7.37	0.70	5.34	5.28	480	0.13	2.7
2013	3-2-9	4.2	10.5	1.00	5.18	5.76	580	0.29	5.1
2013	3-2-10	4.5	17.7	1.55	9.47	10.2	850	0.30	3.8
2013	3-3-1	4.2	20.9	1.74	10.8	8.87	920	0.92	7.1
2013	3-3-2	4.7	10.6	0.97	7.60	5.42	610	0.07	1.5
2013	3-3-3	4.6	15.2	1.49	10.8	15.7	990	0.15	2.6
2013	3-3-4	4.4	10.9	0.97	5.68	6.91	570	0.18	3.1
2013	3-3-5	5.1	12.8	1.19	3.91	6.98	460	0.00	0.6
2013	3-3-6	4.2	11.5	0.95	7.38	5.19	580	0.48	5.5
2013	3-3-7	4.6	10.6	0.92	4.00	4.21	470	0.03	1.6
2013	3-3-8	4.7	18.4	1.67	8.56	11.6	850	0.13	2.0
2013	3-3-9	4.6	11.6	1.05	7.74	4.97	550	0.06	1.5
2013	3-3-10	4.8	13.5	1.28	7.62	3.71	660	0.03	1.2
2013	3-4-1	4.3	13.8	1.16	5.89	4.52	590	0.18	4.6
2013	3-4-2	4.6	12.4	1.15	6.54	5.59	570	0.05	1.4
2013	3-4-3	4.2	10.8	0.88	7.01	4.73	440	0.24	3.2
2013	3-4-4	4.3	11.0	0.94	5.30	3.36	510	0.20	4.3
2013	3-4-5	4.7	34.8	3.14	17.5	14.0	1410	0.16	2.7
2013	3-4-6	4.0	6.04	0.62	5.31	3.11	320	0.37	5.1
2013	3-4-7	4.5	32.4	2.48	15.2	7.55	1260	0.34	4.2
2013	3-4-8	4.7	12.6	1.05	8.6	5.24	640	0.06	1.6
2013	3-4-9	5.0	14.1	1.29	10.3	7.52	770	0.01	1.2
2013	3-4-10	4.3	26.5	2.18	13.1	9.77	1070	0.88	6.5
2013	3-5-1	4.4	32.8	3.04	15.5	12.9	1270	0.39	5.5
2013	3-5-2	4.5	19.1	1.48	8.84	4.30	740	0.13	3.2
2013	3-5-3	4.2	29.6	2.42	10.3	7.57	940	0.62	7.0
2013	3-5-4	4.0	12.1	0.99	8.65	7.50	410	0.33	5.7
2013	3-5-5	4.5	11.8	0.96	4.84	7.55	520	0.06	1.6
2013	3-5-6	4.2	25.4	1.77	9.84	6.29	940	0.89	7.0
2013	3-5-7	5.2	39.1	3.12	15.6	12.0	1290	0.01	0.4
2013	3-5-8	4.3	29.3	2.24	13.4	8.64	1080	0.87	6.6
2013	3-5-9	4.8	26.4	2.03	9.17	6.27	850	0.06	1.6
2013	3-5-10	4.6	16.9	1.41	9.54	9.48	840	0.12	2.1

[a]TC; total carbon. [b]TN; total nitrogen, [c]Oxalate; acid oxalate extractable. [d]PAC; Phosphate absorption coefficient. .

Appendix Table 8. Physico-chemical properties of soil samples from Kamikawa district.

Year	Sample name	$pH(H_2O)$	TC[a]	TN[b]	Oxalate[c]		PAC[d]	Exchangeable	
					Al	Fe		Al	Acidity
			(g kg^{-1})					$cmol_c$ kg^{-1}	(Y1)
2014	3-2-1	4.8	14.2	1.08	9.90	7.30	720	0.07	1.9
2014	3-2-2	4.5	10.5	0.98	7.02	12.3	620	0.01	1.5
2014	3-2-3	4.3	9.67	0.91	6.45	9.49	580	0.16	3.8
2014	3-2-4	4.4	18.1	1.46	10.2	6.59	870	0.27	2.8
2014	3-2-5	4.7	7.04	0.63	5.06	10.3	370	0.01	0.9
2014	3-2-6	4.5	14.9	1.18	6.34	8.52	700	0.05	1.6
2014	3-2-7	5.2	33.6	2.86	15.2	14.6	1340	0.01	0.9
2014	3-2-8	4.3	11.3	1.03	7.72	9.13	640	0.27	3.6
2014	3-2-9	4.9	22.0	1.72	10.2	7.26	920	0.02	1.0
2014	3-2-10	4.7	16.8	1.31	8.38	13.8	740	0.05	2.3
2014	3-3-1	4.0	17.6	1.44	8.76	9.79	850	0.88	7.4
2014	3-3-2	4.3	8.62	0.79	6.82	10.9	620	0.11	2.6
2014	3-3-3	4.1	8.15	0.75	6.15	8.78	650	0.20	4.0
2014	3-3-4	4.5	9.63	0.75	5.22	11.4	440	0.04	1.0
2014	3-3-5	4.0	13.9	1.02	5.01	10.1	520	0.30	5.2
2014	3-3-6	3.9	8.92	0.83	5.39	9.70	440	0.42	6.3
2014	3-3-7	4.3	14.4	1.07	8.55	10.6	700	0.19	3.0
2014	3-3-8	5.0	25.2	2.35	12.9	16.6	1080	0.01	0.8
2014	3-3-9	4.8	15.3	1.39	7.85	10.3	670	0.01	1.6
2014	3-3-10	4.5	15.7	1.14	9.37	9.39	860	0.11	2.4
2014	3-4-1	4.0	18.8	1.33	8.87	10.9	650	0.39	4.0
2014	3-4-2	4.3	16.0	1.09	6.63	8.76	690	0.04	1.2
2014	3-4-3	4.2	16.8	1.20	7.50	11.3	630	0.11	2.4
2014	3-4-4	4.3	7.96	0.70	5.34	11.6	380	0.02	1.7
2014	3-4-5	5.0	28.6	2.51	14.1	21.4	1060	0.00	0.8
2014	3-4-6	4.8	13.1	1.05	6.55	9.77	550	0.00	0.9
2014	3-4-7	4.7	37.7	2.68	15.8	8.83	1180	0.02	1.0
2014	3-4-8	4.9	22.0	1.56	16.4	6.80	970	0.00	0.7
2014	3-4-9	4.1	20.0	1.41	9.13	9.09	760	0.26	3.5
2014	3-4-10	4.1	13.9	1.22	8.26	9.91	620	0.37	4.1
2014	3-5-1	4.3	18.9	1.49	9.00	11.4	680	0.06	1.6
2014	3-5-2	4.2	10.1	0.86	5.34	10.5	450	0.05	1.5
2014	3-5-3	4.2	11.6	0.88	8.33	16.3	610	0.33	3.1
2014	3-5-4	4.1	10.6	0.88	5.87	12.1	530	0.13	2.9
2014	3-5-5	4.2	10.1	0.94	7.03	9.60	550	0.13	2.2
2014	3-5-6	4.0	22.2	1.58	10.1	7.23	890	0.63	7.1
2014	3-5-7	4.8	22.9	1.92	14.3	20.6	1000	0.03	1.3
2014	3-5-8	4.8	14.5	1.22	11.6	8.63	720	0.01	0.4
2014	3-5-9	4.5	17.8	1.29	6.77	21.2	620	0.03	1.1
2014	3-5-10	4.2	13.7	1.20	9.00	12.4	760	0.35	4.4

[a]TC; total carbon. [b]TN; total nitrogen, [c]Oxalate; acid oxalate extractable. [d]PAC; Phosphate absorption coefficient. .

Appendix Table 9. Soil nutrient concentration of farmer fields in Tokachi district.

Year	Sample name	Soil available		CEC[b]	Soil exchangeable cations			WS-Ca[c]	BS[d]	Ca-S[e]
		P_2O_5	N[a]		Ca	K	Mg			
		(mg kg^{-1})			(cmol$_c$ kg^{-1})				(%)	
2013	1-2-1	308	59.7	34.1	14.9	0.66	2.96	0.98	54.1	43.6
2013	1-2-2	344	40.4	29.8	12.1	0.60	2.16	0.64	49.8	40.5
2013	1-2-3	233	30.6	21.7	12.3	0.94	2.31	0.40	71.6	56.7
2013	1-3-1	416	27.5	33.0	10.2	0.24	1.89	0.34	37.2	30.8
2013	1-3-2	611	36.0	26.2	12.7	1.12	3.38	0.88	65.6	48.4
2013	1-3-3	528	35.3	33.6	12.5	0.80	3.94	1.09	51.2	37.1
2013	1-3-4	243	32.5	21.1	9.32	0.92	1.71	0.33	56.6	44.1
2013	1-3-5	278	33.6	49.2	18.7	0.62	2.75	0.60	44.7	37.9
2013	1-3-6	368	28.0	20.5	7.61	1.09	2.84	0.33	56.4	37.2
2013	1-3-7	216	32.8	49.7	11.8	0.55	1.26	0.30	27.3	23.7
2013	1-3-8	204	20.0	19.1	6.04	0.49	1.05	0.63	39.7	31.7
2013	1-3-9	239	30.6	29.8	7.28	0.61	1.23	0.63	30.6	24.4
2013	1-3-10	268	25.8	29.1	9.16	0.57	2.05	0.29	40.4	31.4
2013	1-4-1	198	38.1	28.2	6.83	0.44	0.85	0.59	28.8	24.2
2013	1-4-2	72	15.5	27.0	9.19	1.14	1.45	0.22	43.6	34.0
2013	1-4-3	138	30.0	27.3	7.17	0.70	1.68	0.33	35.0	26.3
2013	1-4-4	236	31.3	37.7	12.6	0.57	2.45	0.42	41.5	33.5
2013	1-4-5	150	20.4	23.7	8.84	0.51	1.13	0.45	44.2	37.3
2013	1-5-1	142	27.8	18.6	7.16	0.65	1.83	0.50	51.7	38.4
2013	1-5-2	184	25.5	21.1	6.51	0.92	2.51	0.51	47.0	30.8
2013	1-5-3	334	32.5	24.2	6.93	0.69	2.02	0.52	39.8	28.6
2013	1-5-4	275	30.7	28.2	6.30	0.44	0.92	0.36	27.2	22.3
2013	1-5-5	334	36.9	42.1	8.07	0.42	1.12	0.38	22.8	19.1
2013	1-5-6	351	25.6	21.7	5.87	1.27	2.12	0.81	42.7	27.1
2013	1-5-7	350	37.0	48.5	15.1	0.55	2.69	0.41	37.8	31.2
2013	1-5-8	240	40.0	31.5	11.1	0.42	1.18	0.47	40.3	35.2
2013	1-5-9	375	33.6	29.6	7.15	0.51	1.35	0.41	30.4	24.1
2013	1-5-10	178	39.9	26.6	7.27	0.33	0.85	0.39	31.7	27.3
2013	2-3-1	117	32.4	28.9	7.37	0.66	1.37	0.31	32.6	25.5
2013	2-3-2	209	45.0	35.2	13.9	0.43	3.56	0.40	51.0	39.6
2013	2-3-3	261	19.1	19.5	5.42	1.06	1.83	0.81	42.6	27.8
2013	2-3-4	139	21.5	22.8	7.29	0.99	2.03	0.34	45.1	31.9
2013	2-3-5	215	39.1	41.2	16.8	0.55	2.03	0.63	47.2	40.9
2013	2-3-6	397	32.7	41.5	17.5	0.68	2.54	0.92	50.0	42.2
2013	2-3-7	240	33.0	22.8	5.55	0.72	1.99	0.39	36.2	24.3
2013	2-3-8	194	34.0	28.9	7.82	0.57	1.63	0.32	34.6	27.0
2013	2-3-9	133	47.6	22.0	8.32	0.41	1.14	0.48	44.9	37.9
2013	2-3-10	273	34.8	36.3	12.0	1.07	3.23	0.19	44.8	33.0
2013	2-4-1	102	39.3	25.0	8.08	0.37	1.12	0.43	38.3	32.3
2013	2-4-2	141	63.8	30.8	18.9	0.77	1.79	0.65	69.6	61.3
2013	2-4-3	183	37.4	21.4	6.00	0.47	1.85	0.40	38.9	28.0
2013	2-4-4	117	28.5	19.7	6.29	1.20	1.69	0.19	46.7	32.0
2013	2-4-5	316	30.1	23.7	8.95	0.78	2.07	0.54	49.9	37.9
2013	2-5-1	415	38.7	18.3	4.89	0.62	1.09	0.32	36.1	26.7
2013	2-5-2	408	42.4	49.7	21.4	0.41	3.22	0.61	50.4	43.1

[a] N; hot water extractable N; [b] CEC cation exchange capacity. [c] WS; water soluble cation, [d] BS,; base saturation. [e] Ca-S; calcium saturation.

Appendix Table 10. Soil nutrient concentration of farmer fields in Tokachi district.

Year	Sample name	Soil available		CEC[b]	Soil exchangeable cations			WS-Ca[c]	BS[d]	Ca-S[e]
		P_2O_5	N[a]		Ca	K	Mg			
		(mg kg^{-1})		(cmol$_c$ kg^{-1})					(%)	
2013	2-5-3	220	31.3	26.0	4.75	0.56	1.30	0.44	25.4	18.3
2013	2-5-4	158	36.3	33.1	8.93	1.31	2.22	0.23	37.6	27.0
2013	2-5-5	173	42.0	22.9	6.21	0.35	1.73	0.25	36.2	27.1
2013	2-5-6	292	41.6	38.4	8.63	0.51	0.98	0.71	26.4	22.5
2013	2-5-7	235	29.1	20.0	7.43	0.63	1.02	0.41	45.3	37.1
2013	2-5-8	242	28.6	27.5	8.57	0.54	2.24	0.44	41.3	31.2
2013	2-5-9	192	34.4	22.1	6.63	0.38	1.41	0.33	38.0	29.9
2013	2-5-10	293	42.9	46.7	15.0	0.77	3.34	0.16	40.8	32.0
2014	1-2-1	289	44.6	22.1	6.62	0.98	1.39	0.37	40.8	30.0
2014	1-2-2	160	46.6	28.0	8.11	1.06	1.38	0.64	37.7	29.0
2014	1-2-3	107	32.4	23.4	6.39	0.60	1.73	0.36	37.1	27.2
2014	1-2-4	257	71.4	21.7	6.07	0.83	1.73	0.86	39.8	28.0
2014	1-2-5	108	95.5	15.9	3.47	1.05	1.49	0.75	37.7	21.8
2014	1-2-6	220	27.7	26.8	8.63	0.73	1.98	0.39	42.3	32.2
2014	1-2-7	205	35.9	28.7	6.49	1.19	2.56	0.82	35.7	22.7
2014	1-3-1	191	29.4	31.6	11.7	0.64	1.63	0.42	44.4	37.1
2014	1-3-2	359	34.5	30.9	15.4	0.90	3.09	0.43	62.8	49.9
2014	1-3-3	190	20.8	14.7	4.89	0.84	1.19	0.42	47.0	33.2
2014	1-3-4	281	29.6	21.6	13.4	0.54	1.81	0.32	72.6	61.8
2014	1-3-5	157	21.4	19.1	4.70	0.40	0.64	0.19	30.0	24.5
2014	2-3-1	174	37.1	39.5	10.1	0.51	2.02	0.26	31.9	25.5
2014	2-3-2	163	38.9	45.0	14.5	0.51	2.84	0.30	39.6	32.2
2014	2-3-3	124	20.6	15.4	3.40	0.53	1.19	0.25	33.2	22.0
2014	2-3-4	201	31.4	31.9	9.06	0.89	2.02	0.31	37.5	28.4
2014	2-3-5	130	23.8	23.9	9.71	0.91	1.57	0.42	51.1	40.7
2014	1-4-1	160	43.8	18.3	2.71	0.34	0.61	0.33	20.1	14.9
2014	1-4-2	188	22.1	19.6	11.8	0.69	3.26	0.89	80.6	60.5
2014	1-4-3	128	33.0	20.8	6.03	0.39	1.31	0.26	37.1	28.9
2014	1-4-4	176	44.4	35.4	11.2	0.88	2.00	0.62	40.0	31.8
2014	1-4-5	124	30.9	19.0	9.58	0.74	1.43	0.27	61.9	50.5
2014	2-4-1	308	30.7	14.9	5.03	0.57	1.32	0.19	46.4	33.7
2014	2-4-2	86	31.9	25.3	13.8	0.47	1.83	0.33	63.5	54.4
2014	2-4-3	73	25.5	18.7	4.56	0.65	1.50	0.27	35.8	24.3
2014	2-4-4	148	19.0	14.9	3.19	0.64	1.20	0.22	33.7	21.4
2014	2-4-5	161	38.6	32.1	14.7	1.43	2.97	0.28	59.4	45.6
2014	1-5-1	133	20.7	28.5	6.98	0.43	1.44	0.21	31.0	24.5
2014	1-5-2	219	26.3	20.3	7.10	0.50	2.28	0.45	48.7	35.0
2014	1-5-3	272	25.6	18.9	6.36	0.39	1.30	0.31	42.7	33.7
2014	1-5-4	135	17.4	20.3	6.82	0.44	1.34	0.14	42.4	33.6
2014	1-5-5	342	37.4	36.0	11.1	0.85	2.85	0.59	41.1	30.8
2014	2-5-1	226	33.8	35.0	6.33	0.57	1.59	0.53	24.3	18.1
2014	2-5-2	200	28.4	28.7	11.2	0.80	2.67	0.42	51.0	38.9
2014	2-5-3	335	25.9	33.3	7.18	1.08	2.69	0.18	32.9	21.6
2014	2-5-4	263	34.6	27.2	6.12	0.64	2.21	0.55	33.0	22.5
2014	2-5-5	232	34.8	25.6	8.38	0.64	2.25	0.24	44.1	32.8

[a]N; hot water extractable N; [b]CEC cation exchange capacity. [c]WS; water soluble cation, [d]BS,; base saturation. [e]Ca-S; calcium saturation.

Appendix Table 11. Soil nutrient concentration of farmer fields in Kamikawa district.

Year	Sample name	Soil available		CEC^b	Soil exchangeable cations			$WS\text{-}Ca^c$	BS^d	$Ca\text{-}S^e$
		P_2O_5	N^a		Ca	K	Mg			
		$(mg\ kg^{-1})$		$(cmol_c\ kg^{-1})$					(%)	
2013	3-2-1	475	82.9	14.9	3.57	0.86	1.52	0.48	39.9	23.9
2013	3-2-2	356	33.1	14.8	6.07	0.61	1.57	0.26	55.9	41.1
2013	3-2-3	241	60.7	13.9	4.31	0.81	1.90	0.41	50.6	31.1
2013	3-2-4	506	78.0	12.6	3.84	0.94	1.77	0.65	51.9	30.5
2013	3-2-5	363	72.6	11.9	4.34	0.68	1.53	0.52	54.8	36.3
2013	3-2-6	454	62.6	11.7	5.45	0.67	1.72	0.45	66.8	46.4
2013	3-2-7	649	46.4	24.3	14.7	0.63	2.68	0.38	73.8	60.2
2013	3-2-8	407	38.7	10.7	3.08	0.97	1.26	0.21	49.7	28.8
2013	3-2-9	379	43.9	14.9	3.71	1.00	2.13	0.19	45.8	24.9
2013	3-2-10	351	53.8	13.7	2.91	0.60	1.40	0.17	35.9	21.3
2013	3-3-1	320	51.9	13.3	2.82	0.56	0.96	0.47	32.7	21.2
2013	3-3-2	429	44.3	12.0	4.66	0.77	1.74	0.29	59.8	38.8
2013	3-3-3	194	36.9	14.9	6.45	0.79	2.17	0.30	63.3	43.4
2013	3-3-4	289	58.5	10.9	3.84	0.78	1.38	0.39	54.9	35.2
2013	3-3-5	601	48.6	11.3	6.08	1.27	2.50	0.35	87.3	53.9
2013	3-3-6	333	50.4	11.9	2.77	0.90	1.21	0.32	40.9	23.2
2013	3-3-7	533	46.8	10.9	4.71	0.68	1.69	0.24	64.9	43.2
2013	3-3-8	250	30.9	12.6	4.38	0.37	1.14	0.19	46.6	34.7
2013	3-3-9	691	34.8	10.3	3.88	1.05	1.44	0.07	61.6	37.5
2013	3-3-10	466	36.6	12.0	5.29	0.58	2.07	0.19	66.3	44.2
2013	3-4-1	486	46.9	12.8	3.20	1.05	2.25	0.40	50.6	24.9
2013	3-4-2	349	45.8	12.6	4.86	0.72	1.49	0.23	56.2	38.6
2013	3-4-3	547	32.2	10.9	2.59	0.61	1.46	0.28	42.6	23.7
2013	3-4-4	537	63.4	11.6	4.12	0.92	1.54	0.67	56.6	35.4
2013	3-4-5	300	36.7	20.4	7.41	0.48	1.80	0.36	47.5	36.4
2013	3-4-6	342	32.0	8.1	1.43	0.71	0.86	0.09	37.2	17.7
2013	3-4-7	445	37.5	19.7	4.91	0.41	1.45	0.47	34.4	24.9
2013	3-4-8	551	38.4	14.1	4.60	1.19	1.35	0.07	50.5	32.6
2013	3-4-9	534	47.8	12.5	4.35	1.34	2.60	0.42	66.4	34.8
2013	3-4-10	292	34.5	15.8	2.67	0.50	0.80	0.16	25.2	16.9
2013	3-5-1	333	43.7	20.1	5.42	0.79	1.57	0.32	38.8	27.0
2013	3-5-2	399	43.4	14.7	3.87	0.85	1.83	0.19	44.6	26.3
2013	3-5-3	417	42.3	19.3	4.44	0.53	1.19	0.53	31.9	22.9
2013	3-5-4	624	40.9	12.2	2.20	0.75	1.74	0.25	38.5	18.0
2013	3-5-5	440	50.2	13.4	4.34	0.68	1.51	0.27	48.6	32.3
2013	3-5-6	254	30.3	18.1	3.24	0.45	1.06	0.24	26.3	17.9
2013	3-5-7	555	43.7	25.4	14.1	0.73	2.52	0.35	68.1	55.3
2013	3-5-8	335	38.4	19.2	3.09	0.65	0.63	0.15	22.8	16.1
2013	3-5-9	350	48.2	19.3	7.00	0.76	1.76	0.16	49.2	36.2
2013	3-5-10	386	45.3	15.1	4.26	0.58	1.47	0.32	41.7	28.2

[a] N; hot water extractable N; [b] CEC cation exchange capacity. [c] WS; water soluble cation, [d] BS,; base saturation. [e] Ca-S; calcium saturation.

Appendix Table 12. Soil nutrient concentration of farmer fields in Tokachi district.

Year	Sample name	Soil available		CEC[b]	Soil exchangeable cations			WS-Ca[c]	BS[d]	Ca-S[e]
		P_2O_5	N[a]		Ca	K	Mg			
		(mg kg^{-1})		($cmol_c$ kg^{-1})					(%)	
2014	3-2-1	277	49.0	10.3	3.00	0.87	1.45	0.27	51.8	29.2
2014	3-2-2	445	88.5	12.1	4.78	1.25	2.51	0.66	70.3	39.3
2014	3-2-3	393	80.5	11.9	3.44	1.25	1.86	0.63	55.2	29.0
2014	3-2-4	288	63.5	13.2	4.85	0.74	1.02	0.68	50.0	36.7
2014	3-2-5	498	42.5	7.89	4.08	0.84	1.56	0.35	82.0	51.7
2014	3-2-6	250	72.7	12.3	4.49	0.90	2.03	0.45	60.1	36.4
2014	3-2-7	442	82.4	25.3	14.5	0.83	2.60	0.35	70.8	57.2
2014	3-2-8	333	58.7	13.9	3.79	1.09	1.35	0.37	44.9	27.3
2014	3-2-9	470	58.2	16.5	7.85	1.03	1.80	0.51	64.9	47.7
2014	3-2-10	470	86.1	12.5	3.95	1.11	2.64	0.53	61.4	31.5
2014	3-3-1	291	75.9	13.5	2.25	0.76	1.20	0.47	31.3	16.7
2014	3-3-2	304	53.7	11.6	4.27	0.75	2.07	0.34	61.1	36.7
2014	3-3-3	401	46.1	9.74	2.58	1.19	1.96	0.28	58.8	26.4
2014	3-3-4	330	27.7	8.84	3.82	0.37	1.40	0.19	63.2	43.2
2014	3-3-5	357	50.5	8.64	3.74	0.53	1.80	0.55	70.2	43.2
2014	3-3-6	394	61.0	9.46	2.04	1.01	1.06	0.32	43.4	21.6
2014	3-3-7	343	34.9	9.72	2.63	0.84	1.53	0.15	51.5	27.1
2014	3-3-8	887	41.4	23.9	16.5	0.94	4.22	0.41	90.4	68.9
2014	3-3-9	396	38.7	10.8	5.42	0.95	2.63	0.16	83.4	50.2
2014	3-3-10	190	28.6	10.8	3.89	0.55	1.61	0.14	56.0	36.0
2014	3-4-1	333	29.4	13.7	2.47	0.43	1.23	0.18	30.2	18.0
2014	3-4-2	573	44.7	15.5	6.22	0.84	2.46	0.42	61.2	40.0
2014	3-4-3	408	59.2	13.2	5.06	0.70	1.56	0.54	55.3	38.2
2014	3-4-4	740	37.3	9.47	4.12	0.64	1.60	0.41	67.1	43.5
2014	3-4-5	794	42.3	23.0	11.0	0.61	3.26	0.30	64.7	47.9
2014	3-4-6	603	42.0	12.6	5.48	0.82	1.85	0.39	64.6	43.4
2014	3-4-7	530	42.4	20.5	7.30	0.36	3.61	0.66	54.9	35.5
2014	3-4-8	223	42.9	12.3	4.30	0.61	1.96	0.18	55.8	34.9
2014	3-4-9	359	35.4	14.5	2.11	0.61	1.73	0.13	30.6	14.5
2014	3-4-10	305	26.3	11.2	1.93	0.38	1.33	0.09	32.5	17.3
2014	3-5-1	497	34.7	15.8	4.10	0.36	1.90	0.47	40.2	25.9
2014	3-5-2	251	41.0	10.2	1.53	0.32	1.66	0.30	34.4	15.0
2014	3-5-3	212	29.2	8.23	2.88	0.40	0.84	0.30	50.0	35.0
2014	3-5-4	464	39.7	12.9	2.26	0.26	1.82	0.39	33.6	17.5
2014	3-5-5	445	32.6	11.1	7.63	0.45	1.85	0.28	89.6	68.9
2014	3-5-6	317	48.2	13.6	3.07	0.74	1.95	0.38	42.4	22.6
2014	3-5-7	361	35.3	20.0	2.02	0.56	2.02	0.33	23.0	10.1
2014	3-5-8	190	34.6	10.5	2.31	0.30	1.26	0.18	37.0	22.1
2014	3-5-9	340	59.9	13.1	5.25	0.49	1.28	0.35	53.5	40.0
2014	3-5-10	215	32.4	10.2	2.78	0.43	1.36	0.20	44.9	27.3

[a]N; hot water extractable N; [b]CEC cation exchange capacity. [c]WS; water soluble cation, [d]BS,; base saturation. [e]Ca-S; calcium saturation.

Appendix Table 13. Tuber yields, yield components and quality characteristics of potato tuber samples collected from Tokachi district.

Year	Sample name	Stem number (per plant)	Tuber number (per plant)	Mean tuber weight (g)	Tuber yield (Mg ha^{-1})	Specific gravity	Starch value (%)	Starch yield (Mg ha^{-1})
2013	1-2-1	2.2	9.4	101	38	1.076	13.1	4.6
2013	1-2-2	1.8	6.4	111	36	1.082	14.4	4.8
2013	1-2-3	1.6	7.9	108	42	1.081	14.1	5.5
2013	1-3-1	3.9	15	73	48	1.101	18.4	8.4
2013	1-3-2	3.6	10	77	36	1.084	14.8	5.0
2013	1-3-3	4.1	12	83	47	1.085	15.0	6.6
2013	1-3-4	2.9	12	86	51	1.083	14.6	6.9
2013	1-3-5	3.5	11	99	49	1.092	16.5	7.5
2013	1-3-6	3.4	12	81	45	1.092	16.5	6.9
2013	1-3-7	2.9	10	94	46	1.089	15.9	6.9
2013	1-3-8	3.1	11	86	49	1.089	15.9	7.3
2013	1-3-9	3.0	11	84	46	1.088	15.7	6.7
2013	1-3-10	3.8	12	85	46	1.087	15.4	6.7
2013	1-4-1	2.8	5.8	135	32	1.084	14.8	4.4
2013	1-4-2	3.3	10	101	46	1.087	15.4	6.6
2013	1-4-3	2.7	7.1	137	46	1.080	13.9	6.0
2013	1-4-4	2.8	7.0	97	34	1.085	15.0	4.8
2013	1-4-5	3.1	9.1	89	40	1.106	19.5	7.4
2013	1-5-1	3.2	12	87	46	1.067	11.1	4.6
2013	1-5-2	3.1	8.7	83	34	1.087	15.4	4.9
2013	1-5-3	2.9	9.5	109	47	1.079	13.7	5.9
2013	1-5-4	4.1	11	85	45	1.085	15.0	6.3
2013	1-5-5	4.3	11	89	44	1.080	13.9	5.6
2013	1-5-6	3.3	12	104	48	1.080	13.9	6.2
2013	1-5-7	2.9	8.3	98	39	1.077	13.3	4.7
2013	1-5-8	3.5	9.7	101	46	1.081	14.1	6.1
2013	1-5-9	2.3	8.5	95	37	1.076	13.1	4.5
2013	1-5-10	2.9	8.5	110	54	1.081	14.1	7.1
2013	2-3-1	3.2	11	75	37	1.092	16.5	5.7
2013	2-3-2	4.4	14	85	48	1.091	16.3	7.4
2013	2-3-3	3.0	11	95	46	1.095	17.2	7.5
2013	2-3-4	2.5	10	90	38	1.090	16.1	5.8
2013	2-3-5	3.9	12	87	47	1.094	16.9	7.5
2013	2-3-6	4.9	14	91	54	1.087	15.4	7.9
2013	2-3-7	4.1	12	78	38	1.091	16.3	5.8
2013	2-3-8	3.0	15	89	48	1.092	16.5	7.5
2013	2-3-9	3.8	12	83	44	1.093	16.7	6.9
2013	2-3-10	3.0	12	84	43	1.088	15.7	6.3
2013	2-4-1	2.7	7.2	100	35	1.090	16.1	5.2
2013	2-4-2	1.5	6.2	102	41	1.077	13.3	5.0
2013	2-4-3	3.7	11	76	41	1.081	14.1	5.5
2013	2-4-4	2.2	9.0	114	47	1.087	15.4	6.8
2013	2-4-5	3.6	10	107	35	1.081	14.1	4.5
2013	2-5-1	3.7	12	86	45	1.080	13.9	5.8
2013	2-5-2	3.5	10	89	38	1.090	16.1	5.8

Appendix Table 14. Tuber yields, yield components and quality characteristics of potato tuber samples collected from Tokachi district.

Year	Sample name	Stem number (per plant)	Tuber number (per plant)	Mean tuber weight (g)	Tuber yield (Mg ha^{-1})	Specific gravity	Starch value (%)	Starch yield (Mg ha^{-1})
2013	2-5-3	3.5	11	91	46	1.080	13.9	6.0
2013	2-5-4	2.7	9.5	93	40	1.083	14.6	5.4
2013	2-5-5	3.3	10	88	37	1.078	13.5	4.7
2013	2-5-6	3.4	9.2	103	40	1.078	13.5	5.1
2013	2-5-7	3.1	11	105	54	1.081	14.1	7.1
2013	2-5-8	3.1	9.3	91	43	1.084	14.8	5.9
2013	2-5-9	4.8	12	73	34	1.090	16.1	5.2
2013	2-5-10	2.3	8.5	111	49	1.078	13.5	6.2
2014	1-2-1	2.4	7.5	119	48	1.078	13.5	6.0
2014	1-2-2	2.1	6.2	115	34	1.082	14.4	4.6
2014	1-2-3	1.6	6.3	100	35	1.079	13.7	4.5
2014	1-2-4	1.9	7.2	122	45	1.081	14.1	5.9
2014	1-2-5	2.1	8.6	127	54	1.081	14.1	7.1
2014	1-2-6	1.6	5.3	172	45	1.080	13.9	5.8
2014	1-2-7	2.0	6.3	110	38	1.084	14.8	5.2
2014	1-3-1	3.5	10	103	51	1.085	15.0	7.1
2014	1-3-2	3.7	11	88	46	1.086	15.2	6.5
2014	1-3-3	4.1	11	123	65	1.082	14.4	8.7
2014	1-3-4	3.4	9.3	94	45	1.083	14.6	6.2
2014	1-3-5	2.9	9.9	91	43	1.098	17.8	7.2
2014	2-3-1	3.3	10	112	50	1.100	18.2	8.6
2014	2-3-2	3.1	9.0	88	41	1.079	13.7	5.2
2014	2-3-3	3.3	14	93	49	1.078	13.5	6.1
2014	2-3-4	3.5	9.3	109	40	1.082	14.4	5.4
2014	2-3-5	2.7	10	98	42	1.091	16.3	6.5
2014	1-4-1	3.9	9.9	115	45	1.084	14.8	6.2
2014	1-4-2	3.0	11	116	52	1.082	14.4	6.9
2014	1-4-3	2.7	7.0	120	43	1.092	16.5	6.7
2014	1-4-4	2.3	8.1	135	53	1.081	14.1	7.0
2014	1-4-5	2.9	7.4	117	43	1.083	14.6	5.9
2014	2-4-1	2.6	8.1	113	37	1.087	15.4	5.3
2014	2-4-2	1.9	8.2	124	36	1.086	15.2	5.1
2014	2-4-3	3.1	9.6	89	38	1.086	15.2	5.4
2014	2-4-4	2.8	12	104	51	1.083	14.6	7.0
2014	2-4-5	3.4	8.1	83	27	1.073	12.4	3.1
2014	1-5-1	4.3	11	131	54	1.085	15.0	7.6
2014	1-5-2	3.0	9.5	102	47	1.088	15.7	6.9
2014	1-5-3	2.3	13	89	45	1.086	15.2	6.4
2014	1-5-4	4.0	12	87	42	1.087	15.4	6.0
2014	1-5-5	4.3	12	90	52	1.084	14.8	7.2
2014	2-5-1	4.4	12	98	37	1.080	13.9	4.8
2014	2-5-2	3.2	7.2	107	32	1.081	14.1	4.2
2014	2-5-3	2.6	8.6	99	44	1.075	12.9	5.2
2014	2-5-4	2.9	6.3	132	45	1.080	13.9	5.8
2014	2-5-5	3.7	13	82	38	1.075	12.9	4.5

Appendix Table 15. Tuber yields, yield components and quality characteristics of potato tuber samples collected from Kamikawa district.

Year	Sample name	Stem number (per plant)	Tuber number (per plant)	Mean tuber weight (g)	Tuber yield (Mg ha^{-1})	Specific gravity	Starch value (%)	Starch yield (Mg ha^{-1})
2013	3-2-1	2.4	6.4	90	24	1.088	15.7	3.5
2013	3-2-2	2.2	6.8	73	22	1.081	14.1	2.9
2013	3-2-3	2.7	5.2	112	25	1.079	13.7	3.1
2013	3-2-4	2.1	3.9	134	23	1.069	11.6	2.5
2013	3-2-5	2.3	7.7	129	41	1.081	14.1	5.4
2013	3-2-6	2.4	5.3	94	24	1.081	14.1	3.1
2013	3-2-7	2.1	6.1	87	26	1.096	17.4	4.2
2013	3-2-8	2.3	6.3	122	29	1.072	12.2	3.3
2013	3-2-9	2.0	5.2	122	26	1.072	12.2	2.9
2013	3-2-10	2.0	6.1	155	30	1.078	13.5	3.8
2013	3-3-1	4.4	11	74	41	1.092	16.5	6.3
2013	3-3-2	3.8	9.9	87	38	1.087	15.4	5.5
2013	3-3-3	3.5	7.9	109	38	1.089	15.9	5.6
2013	3-3-4	2.8	7.9	101	33	1.078	13.5	4.1
2013	3-3-5	4.1	13	102	48	1.075	12.9	5.7
2013	3-3-6	3.1	10	96	40	1.080	13.9	5.1
2013	3-3-7	3.7	8.4	91	38	1.087	15.4	5.4
2013	3-3-8	3.4	12	83	51	1.099	18.0	8.7
2013	3-3-9	5.4	14	95	53	1.095	17.2	8.5
2013	3-3-10	2.9	12	76	41	1.090	16.1	6.2
2013	3-4-1	3.3	4.9	180	41	1.077	13.3	5.0
2013	3-4-2	3.0	7.5	114	56	1.082	14.4	7.6
2013	3-4-3	3.3	8.9	113	50	1.085	15.0	7.0
2013	3-4-4	4.4	9.9	130	40	1.080	13.9	5.1
2013	3-4-5	3.2	8.0	92	47	1.090	16.1	7.1
2013	3-4-6	2.6	9.9	114	37	1.092	16.5	5.8
2013	3-4-7	3.7	7.1	132	35	1.092	16.5	5.5
2013	3-4-8	3.1	8.1	139	44	1.089	15.9	6.5
2013	3-4-9	3.0	9.7	104	40	1.090	16.1	6.0
2013	3-4-10	2.9	8.9	142	52	1.095	17.2	8.4
2013	3-5-1	3.7	8.2	121	46	1.083	14.6	6.2
2013	3-5-2	5.5	10	116	50	1.073	12.4	5.7
2013	3-5-3	4.7	7.9	121	39	1.088	15.7	5.8
2013	3-5-4	4.2	10	108	52	1.079	13.7	6.7
2013	3-5-5	3.3	8.7	100	45	1.088	15.7	6.5
2013	3-5-6	3.7	12	80	40	1.084	14.8	5.6
2013	3-5-7	4.5	9.8	95	41	1.091	16.3	6.3
2013	3-5-8	3.7	9.9	105	46	1.089	15.9	6.8
2013	3-5-9	3.6	6.5	129	58	1.081	14.1	7.7
2013	3-5-10	3.5	11	106	54	1.090	16.1	8.2

Appendix Table 16. Tuber yields, yield components and quality characteristics of potato tuber samples collected from Kamikawa district.

Year	Sample name	Stem number (per plant)	Tuber number (per plant)	Mean tuber weight (g)	Tuber yield (Mg ha^{-1})	Specific gravity	Starch value (%)	Starch yield (Mg ha^{-1})
2014	3-2-1	1.8	8.1	110	37	1.075	12.9	4.4
2014	3-2-2	2.4	8.0	93	41	1.072	12.2	4.6
2014	3-2-3	2.2	8.2	106	40	1.076	13.1	4.9
2014	3-2-4	2.4	8.9	107	46	1.071	12.0	5.0
2014	3-2-5	2.0	11	121	56	1.078	13.5	7.0
2014	3-2-6	1.9	6.8	127	43	1.076	13.1	5.2
2014	3-2-7	2.3	8.7	103	41	1.081	14.1	5.4
2014	3-2-8	1.9	8.2	84	32	1.077	13.3	3.9
2014	3-2-9	1.8	8.8	133	54	1.075	12.9	6.4
2014	3-2-10	2.1	8.4	85	34	1.083	14.6	4.7
2014	3-3-1	3.0	10	101	46	1.093	16.7	7.3
2014	3-3-2	3.2	7.6	132	47	1.085	15.0	6.5
2014	3-3-3	2.9	9.8	95	44	1.087	15.4	6.4
2014	3-3-4	3.3	9.9	83	40	1.085	15.0	5.6
2014	3-3-5	2.6	7.9	114	42	1.076	13.1	5.1
2014	3-3-6	2.5	12	95	50	1.076	13.1	6.1
2014	3-3-7	2.1	9.9	94	46	1.086	15.2	6.6
2014	3-3-8	2.6	11.2	96	54	1.087	15.4	7.8
2014	3-3-9	3.5	9.9	109	44	1.092	16.5	6.8
2014	3-3-10	3.1	11	81	44	1.096	17.4	7.1
2014	3-4-1	4.2	9.2	87	36	1.094	16.9	5.7
2014	3-4-2	2.7	6.2	116	36	1.087	15.4	5.3
2014	3-4-3	2.8	7.5	122	39	1.086	15.2	5.6
2014	3-4-4	3.1	9.6	119	50	1.083	14.6	6.8
2014	3-4-5	2.4	8.1	118	49	1.081	14.1	6.5
2014	3-4-6	2.7	7.0	151	49	1.085	15.0	6.8
2014	3-4-7	2.7	8.4	90	35	1.092	16.5	5.4
2014	3-4-8	3.6	9.1	89	33	1.089	15.9	4.9
2014	3-4-9	2.7	9.9	116	47	1.085	15.0	6.7
2014	3-4-10	3.7	8.7	129	53	1.092	16.5	8.2
2014	3-5-1	3.4	10	82	41	1.086	15.2	5.8
2014	3-5-2	3.5	11	83	42	1.088	15.7	6.1
2014	3-5-3	4.1	13	119	68	1.081	14.1	9.0
2014	3-5-4	2.9	9.1	118	52	1.091	16.3	7.9
2014	3-5-5	4.5	11	75	39	1.089	15.9	5.8
2014	3-5-6	2.6	9.9	109	45	1.081	14.1	5.9
2014	3-5-7	3.1	8.8	100	39	1.092	16.5	6.1
2014	3-5-8	3.9	13	83	42	1.082	14.4	5.6
2014	3-5-9	3.3	9.3	105	45	1.091	16.3	6.8
2014	3-5-10	3.7	12	95	45	1.087	15.4	6.4

Appendix Table 17. Growers` fertilizer application rates, tuber nutrient concentration and incidence of blackspot bruise of samples collected from Tokachi district.

Year	Sample name	Fertilizer rates			Tuber nutrient concentration				Blackspot bruise
		N	P_2O_5	K_2O	N	P	K	Ca	
		(Mg ha^{-1})			(g kg^{-1})			(mg kg^{-1})	(%)
2013	1-2-1	120	120	60.0	15.0	1.54	9.12	186	16
2013	1-2-2	85.9	250	100	12.0	1.52	7.24	154	22
2013	1-2-3	78.1	224	80.0	10.7	1.88	8.94	164	36
2013	1-3-1	53.8	200	80.0	8.84	1.57	6.86	134	28
2013	1-3-2	92.6	250	100	12.2	1.61	8.61	153	26
2013	1-3-3	86.5	265	148	13.7	1.82	8.17	139	18
2013	1-3-4	104	242	126	12.8	1.76	8.59	131	16
2013	1-3-5	55.0	266	111	10.8	1.52	7.86	137	26
2013	1-3-6	50.0	250	100	9.36	1.52	8.14	118	12
2013	1-3-7	45.0	225	90.0	10.9	1.68	8.88	124	12
2013	1-3-8	106	251	77.2	11.1	1.95	8.83	138	14
2013	1-3-9	72.0	300	120	10.8	1.27	8.21	122	4
2013	1-3-10	91.5	360	84.0	11.1	2.04	8.67	115	26
2013	1-4-1	111	200	80.0	13.5	2.14	9.95	170	26
2013	1-4-2	78.6	227	118	9.15	2.94	10.9	140	4
2013	1-4-3	107	230	100	10.7	1.90	10.1	174	4
2013	1-4-4	139	200	247	11.0	1.73	8.76	168	0
2013	1-4-5	96.0	240	132	9.34	3.79	10.6	144	6
2013	1-5-1	102	300	120	16.0	1.77	10.7	150	0
2013	1-5-2	138	248	130	12.9	1.46	8.40	124	10
2013	1-5-3	123	225	115	13.1	1.67	9.68	103	12
2013	1-5-4	100	310	140	14.9	1.64	8.47	146	6
2013	1-5-5	169	286	156	14.3	1.84	9.51	204	4
2013	1-5-6	85.3	226	116	12.3	1.86	10.1	112	28
2013	1-5-7	55.0	253	66.0	13.8	1.95	10.4	166	4
2013	1-5-8	72.0	276	120	14.5	1.93	9.21	202	2
2013	1-5-9	97.9	300	70.0	14.2	1.62	9.52	165	22
2013	1-5-10	126	421	99.0	13.7	1.99	8.35	113	14
2013	2-3-1	80.0	250	90.0	10.9	1.33	7.01	94.1	12
2013	2-3-2	212	76	59.0	11.8	1.68	7.34	109	10
2013	2-3-3	60.0	290	180	8.37	1.77	7.87	86.3	0
2013	2-3-4	56.0	184	96.0	9.18	1.65	7.47	96.2	2
2013	2-3-5	48.0	160	100	9.93	1.49	7.66	144	10
2013	2-3-6	60.0	200	78.0	11.1	1.56	8.35	138	10
2013	2-3-7	56.0	184	96.0	10.4	1.54	8.37	91.6	16
2013	2-3-8	48.0	278	96.0	10.7	1.63	7.92	101	32
2013	2-3-9	100	250	80.0	14.0	1.75	7.11	112	6
2013	2-3-10	63.0	252	90.0	11.4	1.73	8.67	97.7	30
2013	2-4-1	69.0	160	100	10.8	1.98	8.74	131	14
2013	2-4-2	80.0	250	100	14.0	2.14	11.1	218	14
2013	2-4-3	101	250	90.0	11.6	1.89	9.71	124	24
2013	2-4-4	63.0	252	90.0	9.65	2.33	10.0	119	36
2013	2-4-5	80.0	250	100	11.8	2.31	10.1	146	22
2013	2-5-1	77.0	253	132	12.1	2.37	9.01	114	28
2013	2-5-2	112	230	120	14.1	2.03	9.31	212	10

Appendix Table 18. Growers` fertilizer application rates, tuber nutrient concentration and incidence of blackspot bruise of samples collected from Tokachi district.

Year	Sample name	Fertilizer rates			Tuber nutrient concentration				Blackspot bruise (%)
		N	P_2O_5	K_2O	N	P	K	Ca	
		(Mg ha^{-1})			(g kg^{-1})			(mg kg^{-1})	
2013	2-5-3	66.0	286	132	13.0	2.05	10.2	119	14
2013	2-5-4	56.0	176	80.0	11.6	1.60	9.51	119	6
2013	2-5-5	101	250	90.0	13.8	2.06	9.20	113	14
2013	2-5-6	130	242	77.0	14.2	2.02	10.2	190	12
2013	2-5-7	136	287	92.0	14.0	2.08	9.97	147	16
2013	2-5-8	143	240	130	13.4	1.72	8.46	130	26
2013	2-5-9	70.0	260	120	14.0	1.82	8.37	115	24
2013	2-5-10	63.0	252	90.0	14.3	2.03	10.9	153	4
2014	1-2-1	54.0	225	90.0	12.1	1.75	9.07	155	4
2014	1-2-2	60.0	250	100	10.4	1.62	8.45	115	20
2014	1-2-3	48.0	224	80.0	11.2	1.45	8.96	109	6
2014	1-2-4	63.0	152	112	11.2	1.80	8.08	144	2
2014	1-2-5	60.0	260	100	13.7	1.70	8.44	98.7	4
2014	1-2-6	60.0	300	120	10.1	1.84	8.67	103	8
2014	1-2-7	66.0	246	126	8.60	1.74	8.57	120	14
2014	1-3-1	45.0	225	90.0	9.59	2.01	9.28	106	10
2014	1-3-2	50.0	250	100	10.6	2.39	9.55	115	2
2014	1-3-3	60.0	250	100	10.7	2.11	9.46	92.8	10
2014	1-3-4	60.0	250	80.0	11.3	2.08	7.96	125	18
2014	1-3-5	72.0	360	84.0	9.49	1.77	7.62	72.2	26
2014	2-3-1	56.0	224	80.0	10.1	1.65	7.34	89.0	26
2014	2-3-2	85.0	243	18.0	12.6	2.00	9.42	119	4
2014	2-3-3	60.0	290	80.0	9.1	2.08	9.24	72.0	16
2014	2-3-4	56.0	184	96.0	14.3	2.40	7.18	111	10
2014	2-3-5	56.0	184	96.0	10.8	1.84	8.29	146	22
2014	1-4-1	112	280	126	13.8	2.47	9.47	83.4	20
2014	1-4-2	60.5	226	116	10.8	2.79	10.5	100	0
2014	1-4-3	60.0	230	100	12.1	2.34	9.64	104	24
2014	1-4-4	76.0	203	240	15.0	2.22	10.4	134	16
2014	1-4-5	96.0	240	132	12.1	2.61	9.73	108	8
2014	2-4-1	63.0	207	54.0	10.6	2.98	9.74	110	4
2014	2-4-2	80.0	250	100	10.7	2.28	9.81	108	0
2014	2-4-3	80.0	250	90.0	11.3	1.36	8.85	72.6	8
2014	2-4-4	70.0	230	60.0	12.4	2.34	10.7	66.7	2
2014	2-4-5	80.0	250	100	15.8	2.41	11.2	163	0
2014	1-5-1	60.0	300	70.0	14.5	2.29	10.0	113	36
2014	1-5-2	55.0	205	105	12.1	2.24	9.43	123	6
2014	1-5-3	66.0	246	126	11.3	2.58	9.54	100	18
2014	1-5-4	66.0	330	77.0	11.5	1.98	8.33	94.1	18
2014	1-5-5	55.0	253	66.0	14.2	2.28	9.76	166	2
2014	2-5-1	80.5	265	69.0	15.4	1.90	9.94	146	4
2014	2-5-2	81.0	216	117	15.9	1.93	10.1	115	6
2014	2-5-3	56.0	224	80.0	13.9	2.19	11.0	136	4
2014	2-5-4	90.0	240	130	16.5	2.56	9.69	108	2
2014	2-5-5	80.0	250	90.0	15.9	2.13	10.8	159	18

Appendix Table 19. Growers` fertilizer application rates, tuber nutrient concentration and incidence of blackspot bruise of samples collected from Kamikawa district.

Year	Sample name	Fertilizer rates			Tuber nutrient concentration				Blackspot bruise (%)
		N	P_2O_5	K_2O	N	P	K	Ca	
		(Mg ha^{-1})			(g kg^{-1})			(mg kg^{-1})	
2013	3-2-1	134	240	168	15.6	2.01	9.26	87.6	8
2013	3-2-2	114	108	78.0	16.0	2.39	9.00	128	2
2013	3-2-3	123	200	140	14.4	1.80	8.82	133	4
2013	3-2-4	158	252	154	16.1	2.65	10.8	133	0
2013	3-2-5	150	240	168	13.6	2.16	8.87	133	8
2013	3-2-6	134	240	168	14.3	2.69	9.58	142	0
2013	3-2-7	112	200	100	14.0	2.03	8.51	132	6
2013	3-2-8	120	240	168	13.7	2.51	10.4	115	2
2013	3-2-9	120	240	168	16.3	2.35	10.9	127	2
2013	3-2-10	100	200	140	12.9	2.42	10.2	122	18
2013	3-3-1	120	300	156	13.5	2.05	7.92	117	12
2013	3-3-2	114	108	78.0	13.7	2.53	10.3	151	2
2013	3-3-3	143	240	168	12.5	1.69	8.72	115	12
2013	3-3-4	138	216	132	16.0	2.57	10.2	155	0
2013	3-3-5	93.8	160	112	14.3	3.25	11.2	194	0
2013	3-3-6	142	200	140	14.0	2.21	9.63	168	8
2013	3-3-7	134	240	168	14.2	2.58	8.28	143	6
2013	3-3-8	112	200	100	11.2	1.60	6.51	102	26
2013	3-3-9	80.0	200	140	9.62	2.54	8.93	111	32
2013	3-3-10	100	200	140	12.5	2.32	9.25	127	4
2013	3-4-1	143	240	168	16.7	2.87	11.3	135	28
2013	3-4-2	114	200	140	16.8	2.93	9.86	130	32
2013	3-4-3	142	200	140	12.6	2.97	10.6	124	4
2013	3-4-4	190	320	242	15.2	2.99	10.9	198	24
2013	3-4-5	112	200	100	11.2	2.13	9.12	162	24
2013	3-4-6	80.0	160	112	10.8	2.98	10.5	96.3	44
2013	3-4-7	80.0	144	56.0	11.4	2.20	9.18	138	24
2013	3-4-8	80.0	200	140	12.3	3.26	11.7	132	42
2013	3-4-9	105	222	156	12.5	2.62	10.3	110	50
2013	3-4-10	110	220	154	11.6	2.18	9.65	111	20
2013	3-5-1	89.2	144	56.0	16.2	2.06	11.0	143	2
2013	3-5-2	143	240	168	15.8	2.85	12.9	130	2
2013	3-5-3	158	252	154	13.6	1.68	9.10	121	6
2013	3-5-4	142	200	140	14.0	3.00	11.6	122	0
2013	3-5-5	144	260	182	11.5	2.46	9.56	136	16
2013	3-5-6	90.0	180	130	12.9	2.28	9.42	89.4	12
2013	3-5-7	122	220	110	11.5	2.14	9.53	198	20
2013	3-5-8	80.0	200	140	11.3	2.08	9.27	101	34
2013	3-5-9	143	240	168	13.2	2.23	11.3	110	6
2013	3-5-10	120	240	168	12.0	2.20	9.72	124	4

Appendix Table 20. Growers` fertilizer application rates, tuber nutrient concentration and incidence of blackspot bruise of samples collected from Kamikawa district.

Year	Sample name	Fertilizer rates			Tuber nutrient concentration				Blackspot bruise (%)
		N	P_2O_5	K_2O	N	P	K	Ca	
		(Mg ha^{-1})			(g kg^{-1})			(mg kg^{-1})	
2014	3-2-1	84.0	210	147	12.7	2.01	9.12	53.4	26
2014	3-2-2	63.3	121	85.0	14.5	2.26	9.26	149	4
2014	3-2-3	100	200	183	10.3	1.91	7.92	118	6
2014	3-2-4	140	252	154	13.5	1.90	10.0	165	8
2014	3-2-5	100	200	140	15.1	2.65	8.36	111	8
2014	3-2-6	110	220	154	11.4	2.10	9.61	106	0
2014	3-2-7	100	200	80.0	11.9	2.24	10.2	138	0
2014	3-2-8	110	220	154	13.4	2.29	9.03	69.9	28
2014	3-2-9	100	360	140	11.6	1.84	9.25	120	2
2014	3-2-10	120	240	168	11.3	2.11	8.53	104	26
2014	3-3-1	120	180	156	13.2	1.85	7.19	46.4	18
2014	3-3-2	63.3	121	85.0	11.6	2.29	8.33	110	16
2014	3-3-3	100	200	183	10.1	2.41	8.23	62.2	26
2014	3-3-4	120	216	132	14.4	2.04	9.57	70.6	0
2014	3-3-5	100	200	140	14.3	2.58	7.71	106	12
2014	3-3-6	80.0	160	112	13.3	2.57	8.06	75.4	12
2014	3-3-7	80.0	130	50.0	12.1	1.98	8.77	64.3	8
2014	3-3-8	100	200	80.0	10.4	2.53	8.62	96.8	6
2014	3-3-9	80.0	200	140	10.9	2.15	8.26	67.9	8
2014	3-3-10	120	240	168	9.6	1.63	7.99	55.6	16
2014	3-4-1	100	200	140	11.1	2.60	8.96	96.4	4
2014	3-4-2	100	200	140	12.2	3.05	9.82	146	6
2014	3-4-3	80.0	160	112	12.9	2.86	10.8	153	8
2014	3-4-4	100	200	140	12.8	3.50	9.66	142	20
2014	3-4-5	110	220	88.0	12.2	2.94	10.1	129	10
2014	3-4-6	100	360	140	12.9	3.49	11.4	172	26
2014	3-4-7	85.0	153	59.5	10.5	2.53	8.74	101	18
2014	3-4-8	80.0	200	140	11.7	2.56	9.72	75.0	10
2014	3-4-9	80.0	130	50.0	13.0	2.36	10.4	69.8	20
2014	3-4-10	100	200	140	9.49	2.87	9.73	67.7	22
2014	3-5-1	80.0	144	56.0	14.6	2.45	9.25	124	16
2014	3-5-2	100	200	183	12.6	2.65	9.74	87.6	20
2014	3-5-3	140	252	154	12.5	2.10	10.1	91.4	22
2014	3-5-4	80.0	160	112	14.2	2.74	8.05	107	16
2014	3-5-5	110	220	154	11.5	2.88	9.40	89.8	12
2014	3-5-6	100	200	140	14.2	2.53	9.87	60.8	12
2014	3-5-7	110	220	88.0	12.8	1.95	7.87	118	6
2014	3-5-8	80.0	200	140	13.2	2.65	8.83	68.0	8
2014	3-5-9	100	360	140	11.8	2.09	8.81	111	38
2014	3-5-10	120	240	168	11.6	2.26	8.63	68.3	32